

KINEMATIC STUDIES OF BOMEX - PHASE IV

Richard A. Anawalt

KINEMATIC STUDIES OF BOMEX - PHASE IV

by

Richard A. Anawalt

B.S., Miami University
(1963)

M.S., Naval Postgraduate School
(1969)

SUBMITTED IN
PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE
DEGREE OF MASTER OF SCIENCE

at the
MASSACHUSETTS INSTITUTE OF
TECHNOLOGY

June, 1971

KINEMATIC STUDIES OF BOMEX - PHASE IV

By

Richard A. Anawalt

Submitted to the Department of Meteorology on 18 June
1971 in partial fulfillment of the requirements for the
degree of Master of Science.

Abstract

Computations of divergence and vorticity are made by the triangular method for six 100-mb layers (1000-400 mb) for those observation times (11) when wind data is available from eight stations in the BOMEX region during the period 11-28 July 1969 (Phase IV). The results are compared to cloudiness from satellite pictures. Contemporary correlation coefficients between vorticity and divergence in the six layers ranged from $-.19$ to $+.26$. The correlation in the lowest layer (1000-900 mb) (where Ekman theory predicts a large (~ -1.0) negative correlation) was $-.19$. The vorticity and divergence values had the same sign in approximately 50% of the sample. Despite the low values for the correlation coefficients, the comparison of the results to satellite pictures is encouraging in that convergence and cyclonic vorticity are associated with regions of maximum cloudiness. When algebraic means are computed within each of the six layers, the results indicate the vorticity has the same order of magnitude from 1000 to 400 mb while the divergence decreases by an order of magnitude above 800 mb. The divergence and vorticity were of the same order of magnitude from 1000 to 800 mb. Computation of mean magnitudes showed no such decrease in the order of magnitude of the divergence above 800 mb.

All triangles were subjectively classified as either disturbed, undisturbed or neither. Comparison of the mean values of divergence and vorticity within layers by the Student's t-test revealed there were significant (1% level) differences between the vorticity results for disturbed and undisturbed conditions and the results for divergence indicate significant differences at the 2% level in the lowest layer and at the 10-20% levels in the next two layers (900-700 mb) thereby supporting the CISK hypothesis.

Thesis Supervisor: Frederick Sanders

Title: Professor of Meteorology

ACKNOWLEDGEMENTS

The author is grateful to the United States Navy for the opportunity to pursue this work at M.I.T. and to NOAA for partial support under Grant No. E22-37-71(G). Special thanks go to Professor Frederick Sanders for his encouragement and guidance throughout the study. Thanks are also due to Mrs. Terri Berker who spent many hours punching data cards, Miss Isabelle Kole for drafting the figures and Miss Kate Higgins who typed the manuscript. Finally, the author thanks Cdr. F.R. Williams (U.S. Navy), Lt. Col. Paul Janota (U.S. Air Force) and Miss Colleen Leary for their helpful discussions and suggestions during the research.

Table of Contents

	<u>Page</u>
List of Figures	5
List of Tables	6
Introduction	7
Application	13
Data Utilized	15
Results	18
Conclusions	38
Appendices	
A. The Computation Procedure	41
B. Tables 3 to 12	43
References	52

List of Figures

<u>Figure</u>	<u>Title</u>	<u>Page</u>
1	Geographic arrangement of fixed stations during BOMEX, phase IV	8
2	Triangular divisions with expanded BOMEX array	11
3	Analyzed results of divergence and vorticity for 14/00Z, layer 1, with cloud cover for 13/1817Z	19
4	Same as figure 3 except layer 2	20
5	Analyzed results of divergence and vorticity for 14/12Z, layer 1, with cloud cover for 14/1136Z	21
6	Same as figure 5 except layer 2	22
7	Analyzed results of divergence and vorticity for 25/12Z, layer 1, with cloud cover for 25/1532Z	24
8	Same as figure 7 except layer 2	25
9	Analyzed results of divergence and vorticity for 26/00Z, layer 1, with cloud cover for 25/1826Z	26
10	Same as figure 9 except layer 2	27
11	Analyzed results of divergence and vorticity for 26/12Z, layer 1, with cloud cover for 26/1233Z	28
12	Same as figure 11 except layer 2	29

List of Tables

<u>Table</u>	<u>Content</u>	<u>Page</u>
1	Summary of mean values of divergence and vorticity.	32
2	Summary of mean values of divergence and vorticity within categories of degree of disturbance.	34
3	Latitude and longitude of data stations.	43
4	Designation of triangles.	43
5	Latitude and longitude of triangle centroids.	44
6	Subjective evaluation of disturbed nature of each triangle for each data time.	45
7	Results for 1000-900 mb.	46
8	Results for 900-800 mb.	47
9	Results for 800-700 mb.	48
10	Results for 700-600 mb.	49
11	Results for 600-500 mb.	50
12	Results for 500-400 mb.	51

INTRODUCTION

The Barbados Oceanographic and Meteorological Experiment (BOMEX) was carried out from 3 May to 28 July 1969 east of the island of Barbados (13.1 N, 59.5 W). The entire experiment was divided into four phases and it is phase IV (11-28 July 1969) with which this thesis is concerned. This phase of BOMEX was designed to explore large convective systems in the tropical Atlantic. The overall plans, description and some early results of BOMEX activities are described in Davidson (1968), Cook (1969), Kuettner and Holland (1969), U.S. Dept. of Commerce (1969), Holland (1970), Friedman and McFadden (1970) and BOMEX Bulletins numbers 1-9.

There were five "stationary" ships plus the island of Barbados to take observations during phase IV. The geographic arrangement is shown in figure 1. In addition, there were numerous aircraft available which were equipped to take meteorological observations. During the period 11-28 July 1969 there were six synoptic-scale disturbances which passed through the BOMEX array as described by Fernandez-Partagas and Estoque (1970), one of which was classified as a tropical depression (22-27 July). The remaining disturbances were classified as follows: 3 weather systems, 1 complex weather situation and 1 middle-level weakening cyclonic circulation (Fernandez-Partagas and Estoque, 1970). This crude method of classifying tropical disturbances suggests a definite lack of understanding of the disturbance-producing mechanisms in the tropics.

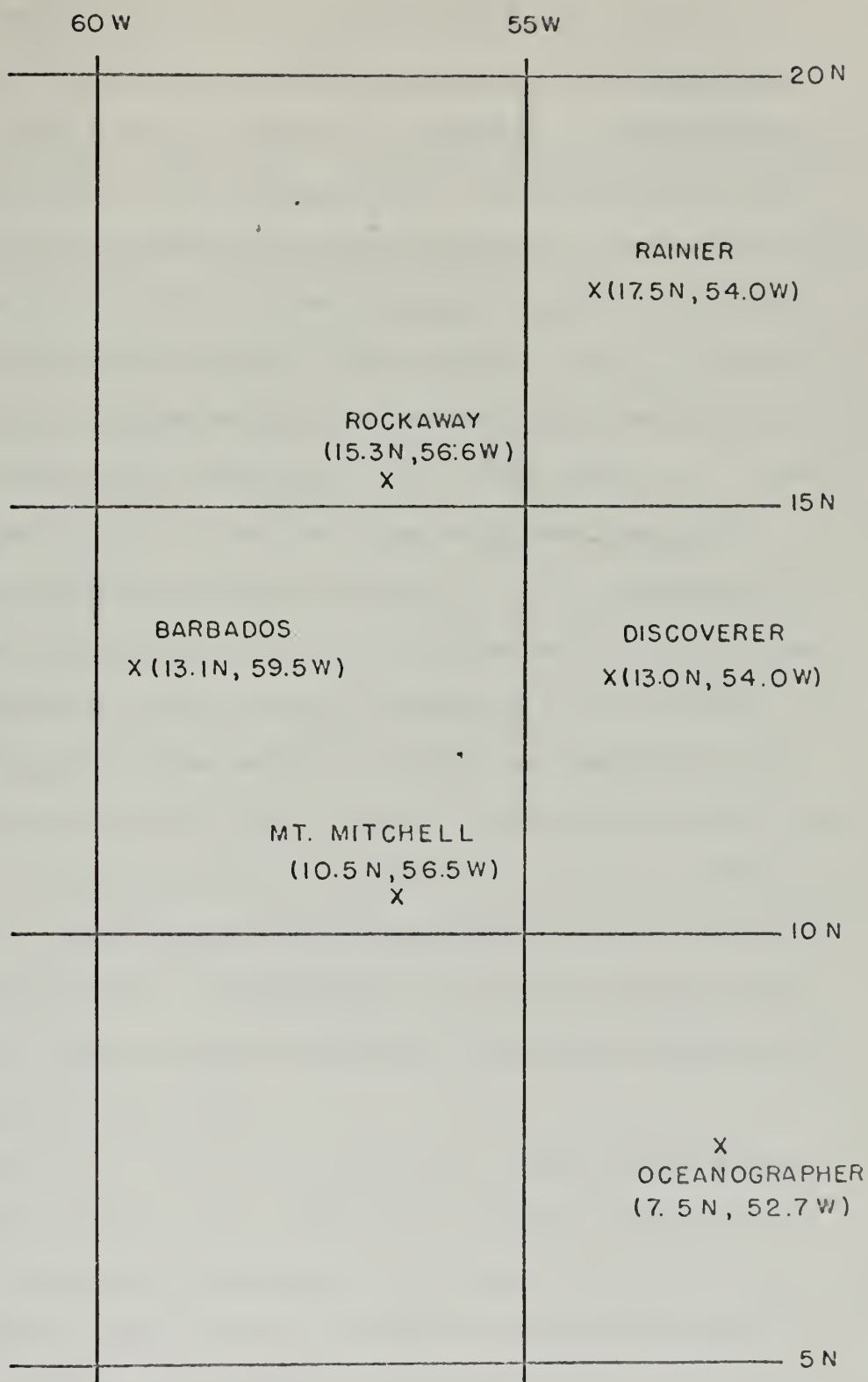


Fig. 1. Geographic arrangement of fixed stations during BOMEX, phase IV (Scale, $1/2'' = 1^\circ$).

In looking for causes of tropical disturbances, Charney and Eliassen (1964) and Charney (1969) have proposed conditional instability of the second kind (CISK) as a mechanism for establishment of low-level water-vapor convergence and a resulting upward motion at the top of the boundary layer, thus leading to a release of latent heat above the boundary layer which provides the source of energy for maintaining a disturbance. CISK requires an initial increase in the surface relative vorticity as the initiating impulse to set up the boundary-layer convergence. Gray (1968) found a ". . . strong association of tropical disturbance and storm development with synoptic-scale surface relative vorticity . . .". The idea of CISK as a cause of disturbances in the tropics has met with wide approval, but observational evidence of such a mechanism is not available; in fact, how to obtain observations to confirm the hypothesis is not readily apparent to the author. Sargeant and Ruttenberg (1970) have included the following as one of the "Specific Atmospheric Objectives" of an international tropical experiment which will probably be conducted in 1974: "In particular, to provide sufficient data to verify or reject present formulations of the CISK mechanism, and to extend such formulations".

Manabe et. al. (1970) have attempted to reproduce the general circulation features of the tropics from a numerical model for the month of January and obtained quite good results. They simulated the convection process by means of "moist-convective adjustment", a process which has the effect of transferring heat energy from lower layers to upper layers, thus creating a cold core in the lower

part of the troposphere and a warm core in the upper troposphere. This process was initiated in the model whenever a layer became saturated and the lapse rate in the layer became super-moist adiabatic.

In an attempt to extend present ideas on tropical convective phenomena, it was decided to use the BOMEX data to look at disturbances in some detail. Although the distance between stations (380-530 km) precludes investigation of small-scale activity, it does provide the necessary data for investigation of the disturbance-scale (i.e., sub-synoptic scale) as well as for comparing differences in conditions between disturbed and undisturbed situations. The relation of the mesoscale structure of the tropics in disturbed vs. undisturbed conditions is now being recognized as one of the most crucial problems to solve in the tropics (Zipser, 1970).

The array of ship and land stations in the BOMEX area is arranged conveniently for application of the triangular method of computing divergence, vertical motion and vorticity as proposed by Bellamy (1949). A modification of Bellamy's method was proposed by Graham (1953) but since the data stations in BOMEX are "fixed" the Bellamy method is appropriate. The results thus obtained are most likely to be representative of the centroid of the triangle (Bellamy, 1949). Figure 2 shows the breakdown of the BOMEX area into eleven triangles with centroids marked by \otimes . Two stations have been added to expand the area of coverage for which data is available twice daily. The major disadvantage of the Bellamy method is the

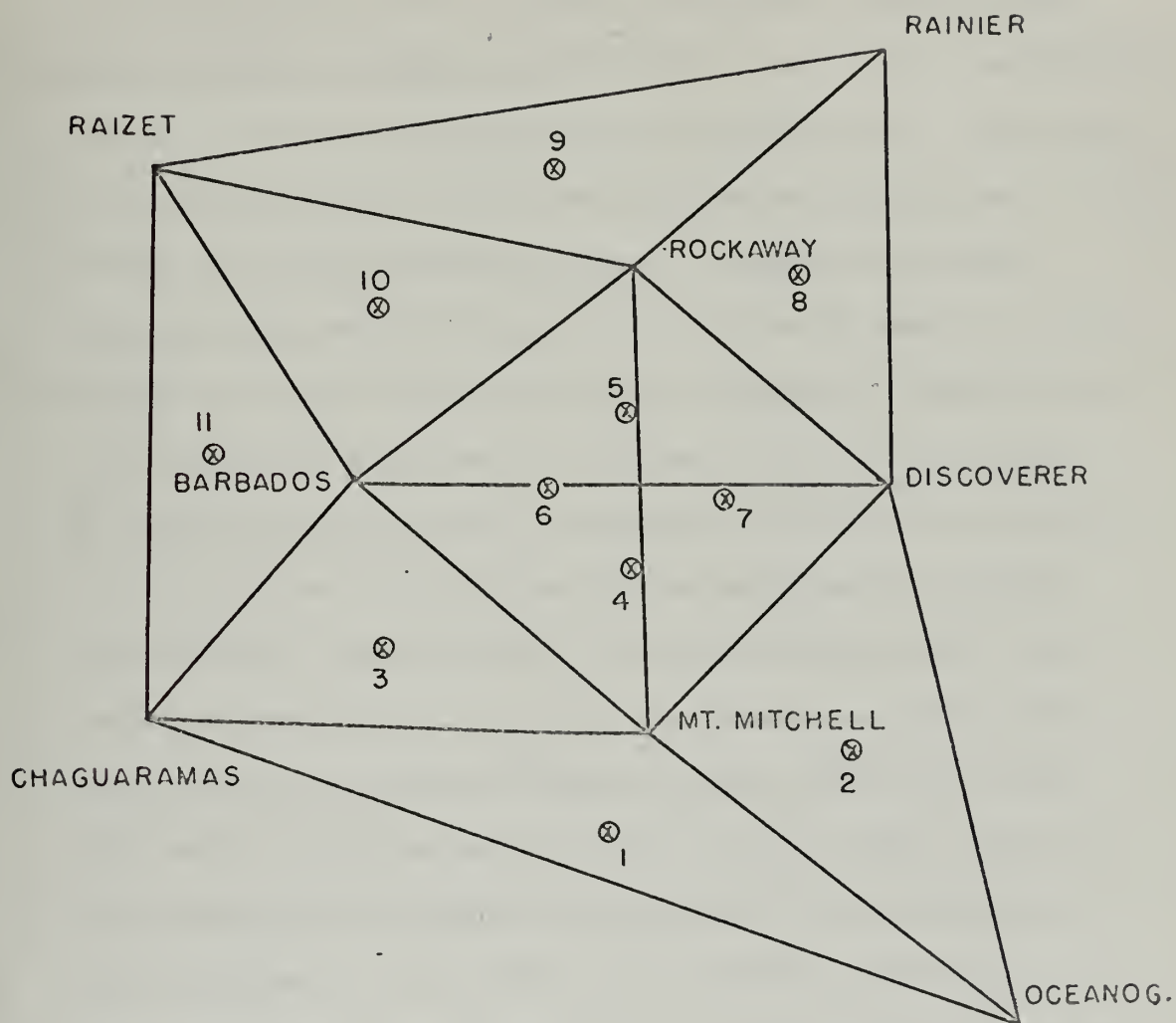


Fig. 2. Triangular divisions with expanded BOMEX array. Numbers at centroids correspond to numbers assigned to that triangle for identification. (Scale: $1/2" = 1^\circ$)

assumption of a linear variation of the wind between vertices of the triangle, an assumption which may yield misleading results in certain cases as shown by Zipser (1965). Successful application of this method has been made by Byers and Rodebush (1948) and Byers and Hull (1949) in thunderstorm studies. Lateef (1967) computed divergence, vertical motion and vorticity fields over a grid covering the Caribbean for a 3-day period during which a low-level easterly wave passed through the grid. He used the pressure-differentiated form of the continuity equation to compute vertical velocities to offset the difficulty of obtaining a large non-zero value for the net divergence in a column. Various other authors who have made computations of divergence, vertical motion and vorticity in the tropics utilizing the continuity equation include Landers (1955), Arnason (1955), Endlich and Mancuso (1963), Kyle (1970) and Arnason et. al. (1963). The computations of Landers (1955) utilized the modified Bellamy method proposed by Graham (1953) while the method used by Arnason et. al. (1963) consisted of extracting wind components at gridpoints from streamline and isotach analyses. Kyle (1970) computed vertical motion using a latitude-longitude grid of monthly mean values of the wind components. Endlich and Mancuso (1963) performed their calculations by the triangular method on triangles varying in area from 22000 to 920000 km^2 in the Caribbean area. In contrast, the triangles shown in figure 2 range in size from approximately 71000 to 105000 km^2 .

APPLICATION

In order to be able to synoptically analyze the results, only those times when winds for all eight stations were available were used. This limited the data to 00Z and 12Z observations because that is the only data available for Raizet and Chaguaramas which is found in the Northern Hemisphere Data Tabulations (NHDT). This means a possibility of 18 days at twice per day which would yield 36 data sets. However, so much of the ship wind observations were missing that the end result was 11 data sets, and they aren't all quite complete. The observation times finally selected for this study are: 14/00Z, 14/12Z, 18/00Z, 20/00Z, 21/12Z, 22/12Z, 25/12Z, 26/00Z, 26/12Z, 28/00Z and 28/12Z. Tables 3 to 5 in Appendix B summarize the identification of the triangles and the locations of the centroids.

In order to interpret the results in comparison with disturbed or undisturbed situations, a method of classifying the triangles as disturbed or undisturbed is needed. Such a method is available by means of enlargements of ATS-III and ESSA-9 satellite pictures. By tracing the cloud cover in the BOMEX region onto acetate and then projecting the result with an overhead projector, enlargements of the satellite picture can be obtained to almost any scale. For this study the pictures were enlarged to a scale of $1'' = 1^\circ$ of latitude (results presented later are at a scale of $1/2'' = 1^\circ$ of latitude). With a copy of figure 2 at the same scale superimposed on the copy of the satellite picture, a subjective classification of U (undisturbed), D (disturbed) or N (neither disturbed nor undisturbed) was

made for each triangle at each observation time depending on the areal extent of cloud cover for each triangle. Allowances were made for cases when the satellite picture was not at the same time as the observations. The criteria used for the classifications were as follows: U, less than 10% of area covered by clouds; N, less than 50% of area covered by clouds but more than 10%; D, 50% or more of area covered by clouds. Out of a total of 121 such classifications (11 triangles for each of the 11 observation times used) there were 52 = U, 27 = N and 42 = D. The results of this classification are listed in Appendix B, table 6.

Appendix A describes the method of computing divergence and vorticity. In addition to the triangle parameters, the data needed for the computations are the wind direction and wind speed profiles for each of the stations. For this study the winds were obtained at 50-mb intervals from 1000 to 400 mb and then vectorially averaged by 100-mb layers according to the trapezoidal rule, thus resulting in six layers, each containing a vector-mean wind. The vector-mean winds were then used to compute the mean divergence and mean vorticity for each of the six layers of each of the eleven triangles.

DATA UTILIZED

The data utilized for the computations were the u and v wind components at 50-mb intervals from 1000 to 400 mb. The data for Barbados, Raizet and Chaguaramas were used exactly as given in the NHDT. Data for the five "stationary" ships were complicated by the fact that the ships were actually not stationary due to the failure of the mooring lines for all five ships before the beginning of phase IV (BOMAP, 1971). Since it was planned to use the processed rawinsonde observations from the "A₀" (BOMEX Bulletin No. 9, 1971) data reduction process performed at NASA's Mississippi Test Facility, this presents the problem of correcting the winds for ship's motion. A search through ship's logs and course and speed tables provided by BOMAP (BOMAP, 1971) revealed that there were several inconsistencies in regards to the necessary correction. (For example, ship's course before, during and after could not be verified when compared to gyro headings found in the BOOM data [BOMAP, 1971]). Fortunately, however, it appears that this correction is very small (because tabulated ship speeds are small) for all ships except ROCKAWAY. The tabulated ship speeds for ROCKAWAY were as large as 10.5 knots. Due to the uncertainty in such a large correction it was decided to use the data sent by ROCKAWAY via teletype with the idea that the observers on ROCKAWAY made the necessary corrections to the data before sending it.

An additional problem with ROCKAWAY was the inability to acquire the balloon for 6 to 10 minutes after launch (BOMAP, 1971),

as evidenced by the missing winds in the lowest 5000 feet or so. To alleviate this problem the teletype winds were broken down into u, v components and plotted on a vertical logarithmic scale using a standard tropical atmosphere (Schacht, 1946; and Riehl, 1954). The winds at the lowest reported level were then linearly connected to the surface wind and the necessary winds were read off at 50-mb intervals.

Except for specific cases to be noted later, the "A₀" data was used for the remaining ships (at present there is no choice but to use it for Mount Mitchell). The u, v winds were taken directly from the "A₀" data at 50-mb intervals. In a few cases winds were missing at some of the 50-mb intervals (in particular, for DISCOVERER) and in such cases the needed data was obtained by applying techniques similar to that described above for ROCKAWAY. The only corrections made to this data were for RAINIER which had a voltage reference problem. Comment cards acquired from BOMAP on the performance of each individual sounding indicate that the computed wind directions for RAINIER are in error by 140-220°. This is particularly evident if wind directions computed from "A₀" data are compared to wind directions reported in the teletype data. Consequently the error reported by BOMAP was applied to all the wind directions for RAINIER as computed from the "A₀" data. Even though no correction was tabulated for RAINIER at 26/12Z, a correction of 140° was applied based on soundings at times before and after 26/12Z and based on comparisons with the teletype data.

Teletype data was also substituted for "A_o" data in the following three cases for the reasons specified:

21/12Z Oceanographer ; Many winds were missing in the "A_o" data but complete wind data was available in teletype form.

22/12Z Oceanographer; There were no winds in the "A_o" data but complete wind data was available in teletype form.

22/12Z Discoverer; The "A_o" winds were missing at many levels but complete wind data was available in teletype form.

There was no data at all for OCEANOGRAPHER at 28/12Z but there was "A_o" data for 28/10Z and 28/1343Z. In order to complete the data set at 28/12Z, the winds at the two off times were averaged and used in the computations to obtain an approximation to the values for 28/12Z.

A final comment regarding corrections to the island data is necessary. No terrain effects have been considered for Barbados, Raizet and Chaguaramas. As pointed out by Lilly and LaSeur (1956) the nature of a correction at Chaguaramas is very complicated. This was also discussed by Zipser (1965) who made "ad hoc" corrections to the Chaguaramas winds. Zipser's correction to the winds at Raizet amounted to increasing the reported mean wind speed (surface - 850 mb) by 17%. For this study, no corrections have been applied to the reported winds for any of the island stations.

RESULTS

Some of the results of this study are presented in this section in the form of synoptically analyzed charts of the BOMEX region. Vorticity and divergence for layers 1 and 2 (1000-900 mb and 900-800 mb) for five synoptic times are presented in the figures 3-12. Results for all synoptic times used and all layers are presented in tables 7-12 in Appendix B. In addition, figures 3-12 show depictions of cloud cover obtained from ATS-III and ESSA-9 satellite pictures for comparison to the analyzed results which are presented. These depictions were obtained from the satellite pictures as described in the Application section.

The figures presented in this section cover two specific cases: 1) 14 July 1969; Weather system (Fernandez-Partagas and Estoque, 1970) which moved through the northern half of the BOMEX region from east to west and 2) 25-26 July 1969; Tropical depression (Fernandez-Partagas and Estoque, 1970) which emerged from the ITCZ and moved northwest through the BOMEX region.

A comparison of the satellite picture depiction at 14/00Z (keep in mind the satellite picture is for 13/1817Z) with the analysis of divergence and vorticity shows nothing very striking, perhaps due to the relative inactivity in the BOMEX region. Perhaps the most noticeable feature is the convergence which seems to be coming into the region from the east. At 14/12Z the convergence has extended slightly farther into the BOMEX region and appears to be somewhat associated with the region of cloudiness which is approaching from

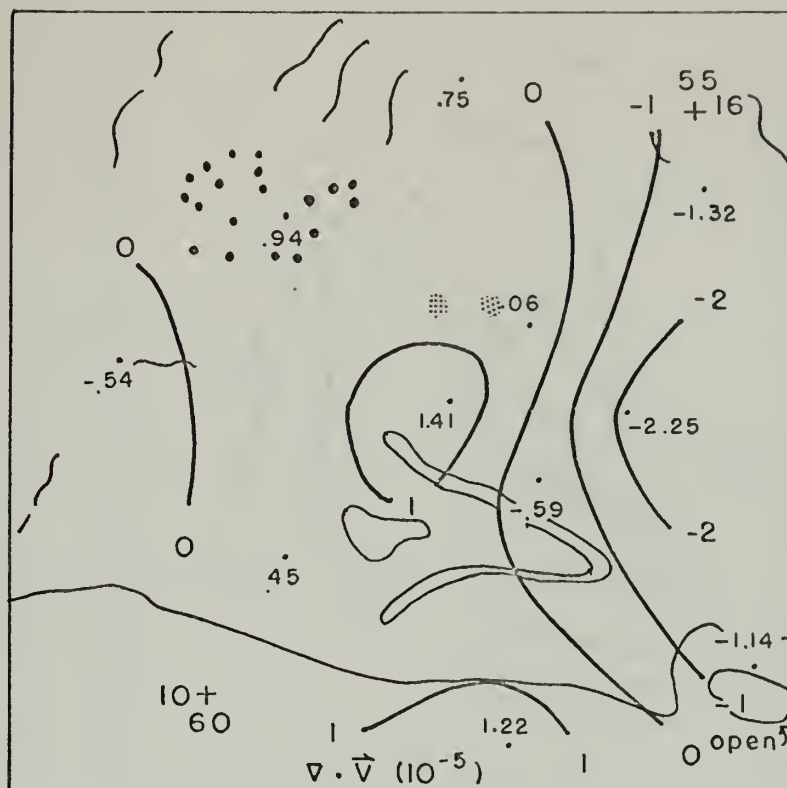
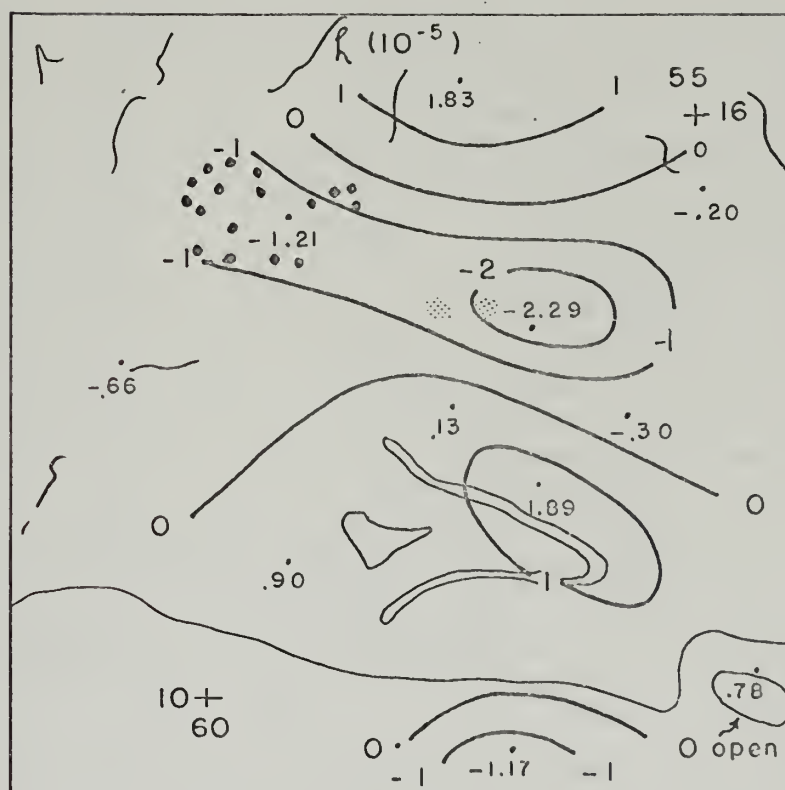


Fig. 3. Analyzed results of divergence and vorticity for 14/00Z, layer 1, with cloud cover for 13/1817 Z



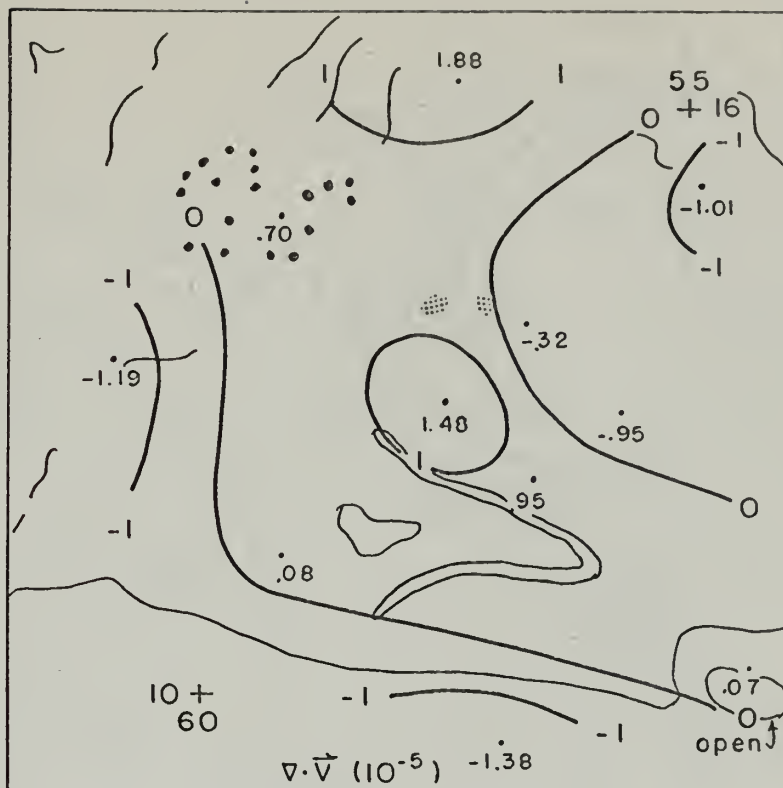
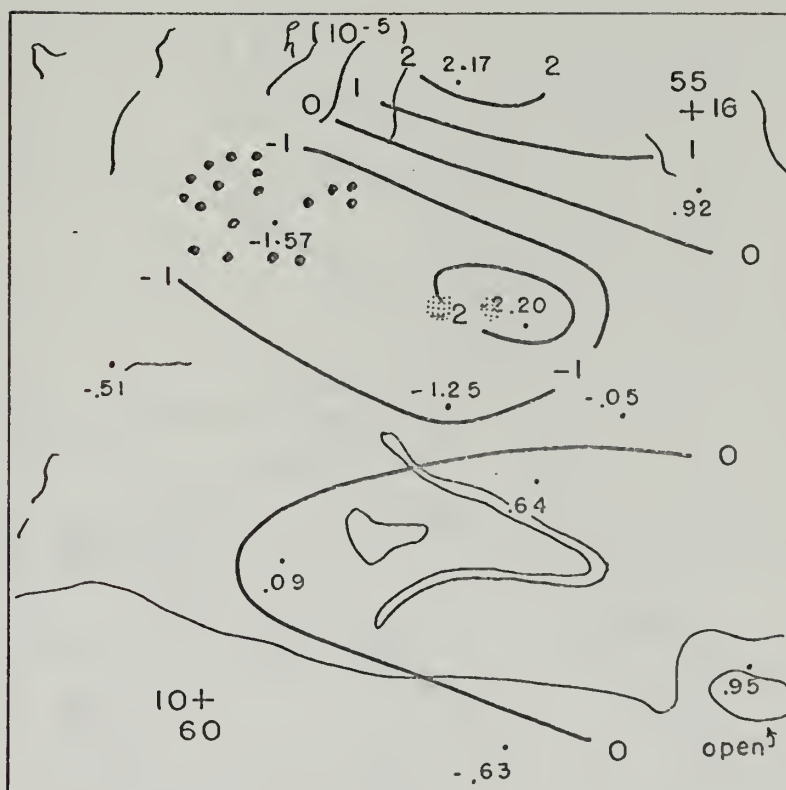


Fig. 4: Same as figure 3 except layer 2.



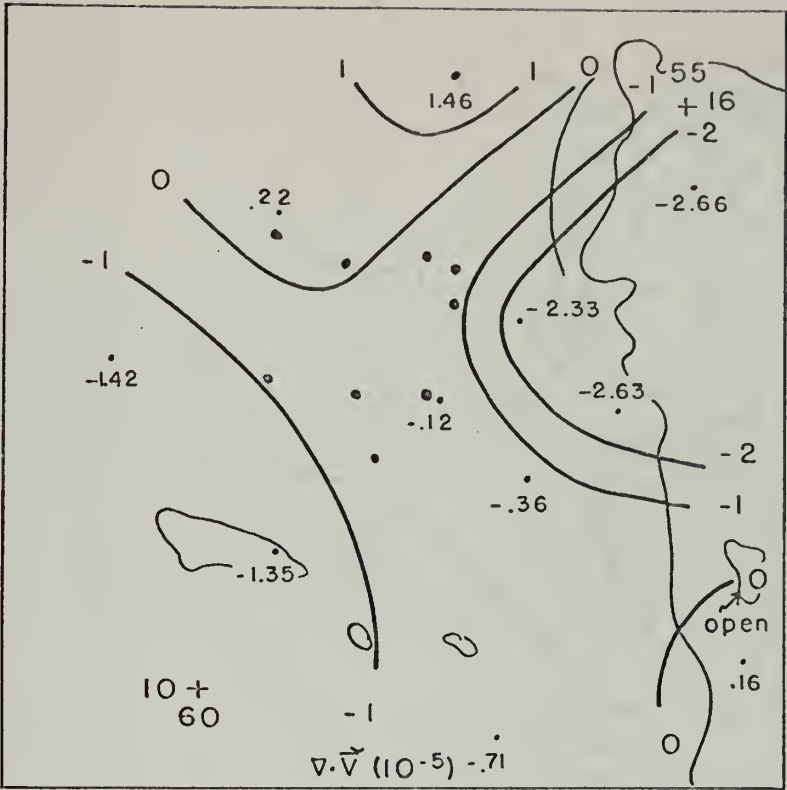
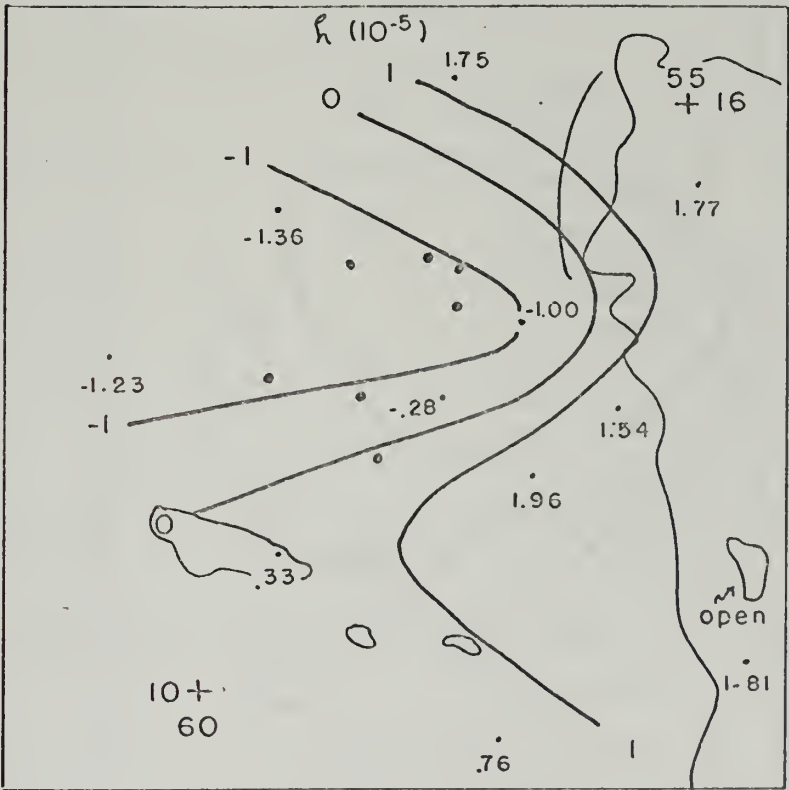


Fig. 5: Analyzed results of divergence and vorticity for 14/12 Z, layer 1, with cloud cover for 14/1136 Z.



the east. Likewise there is a region of cyclonic vorticity which appears to be associated with the cloud system and anticyclonic vorticity out ahead of it.

Comparing the 25/12Z results (the satellite picture reproduction is for 25/1532Z) shows the ITCZ to be associated with the region of strongest convergence. The stipled regions in the cloud depiction correspond to regions on the picture which were very bright. Comparison with the vorticity analysis shows the ITCZ region to be associated with the cyclonic vorticity; however, the orientation of the vorticity lines appears to be transverse to the ITCZ.

For comparison of results at 26/00Z it becomes necessary to use a 25/1826Z satellite picture. Unfortunately there isn't much difference between the 25/15Z and 25/18Z pictures but the difference in the results for divergence and vorticity is considerable. The region of strongest convergence is still associated with the region of maximum cloudiness but now there is also a strong ($\sim 4 \times 10^{-5}$) center of cyclonic vorticity which appears to be located in the ITCZ region.

At 26/12Z the pattern has changed considerably. There is a broad expanse of cloud cover which covers almost the entire BOMEX region. There is a strong (-3.5×10^{-5}) center of convergence in the center of the region and the small region of divergence (13N, 61W) agrees well with a clear region on the satellite picture. The vorticity results are not as good except for the cyclonic vorticity region in the northern half of the BOMEX region.

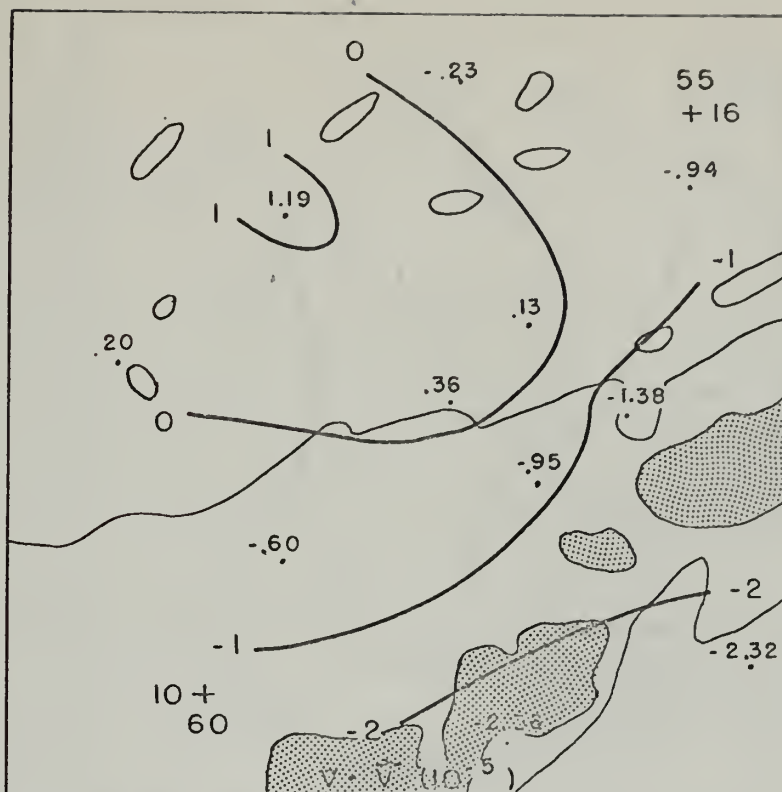
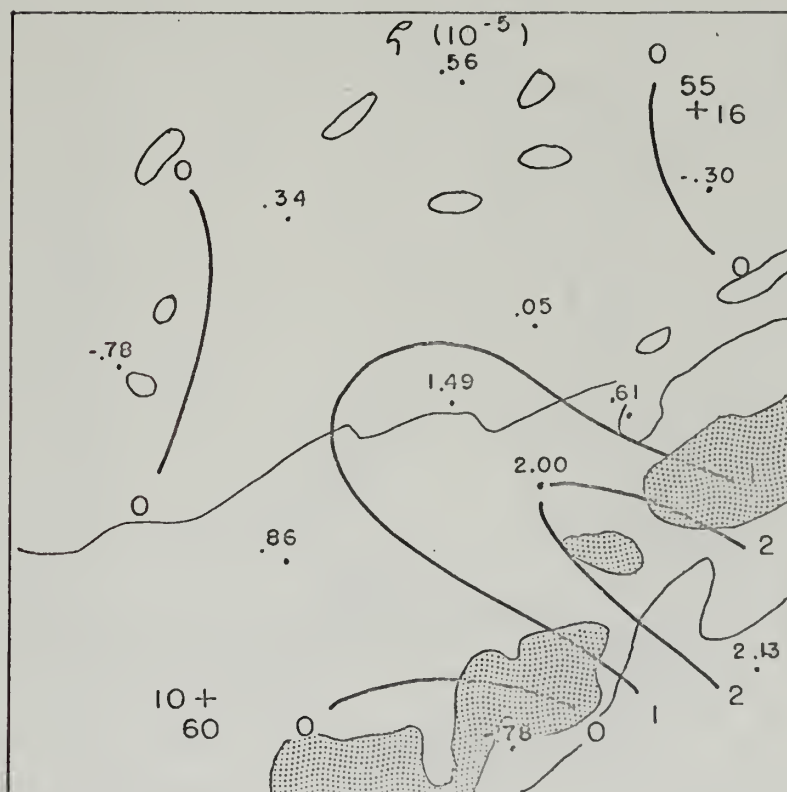


Fig. 7: Analyzed results of divergence and vorticity for 25/12Z, layer 1, with cloud cover for 25/1532Z.



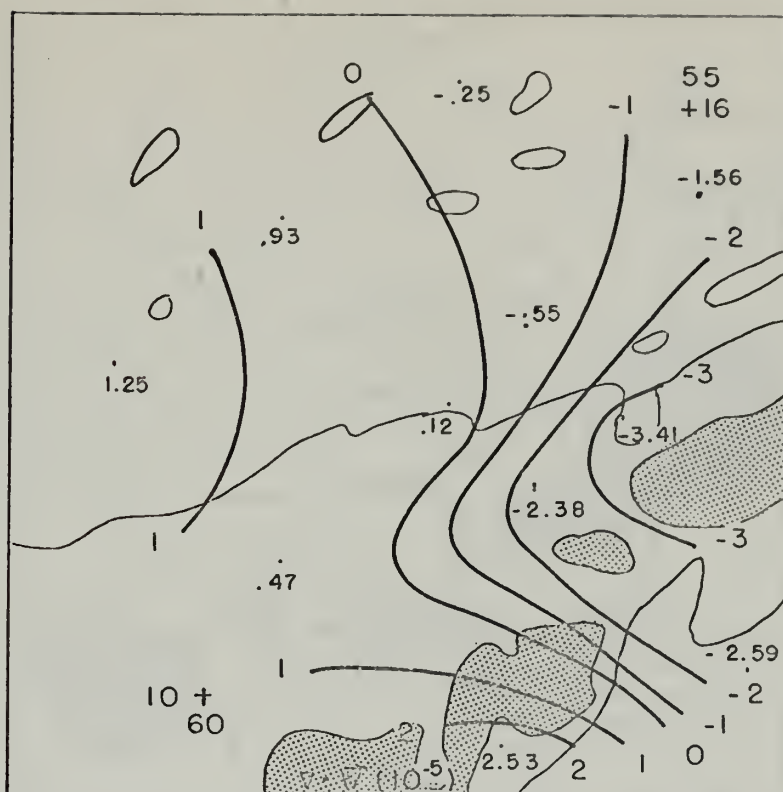
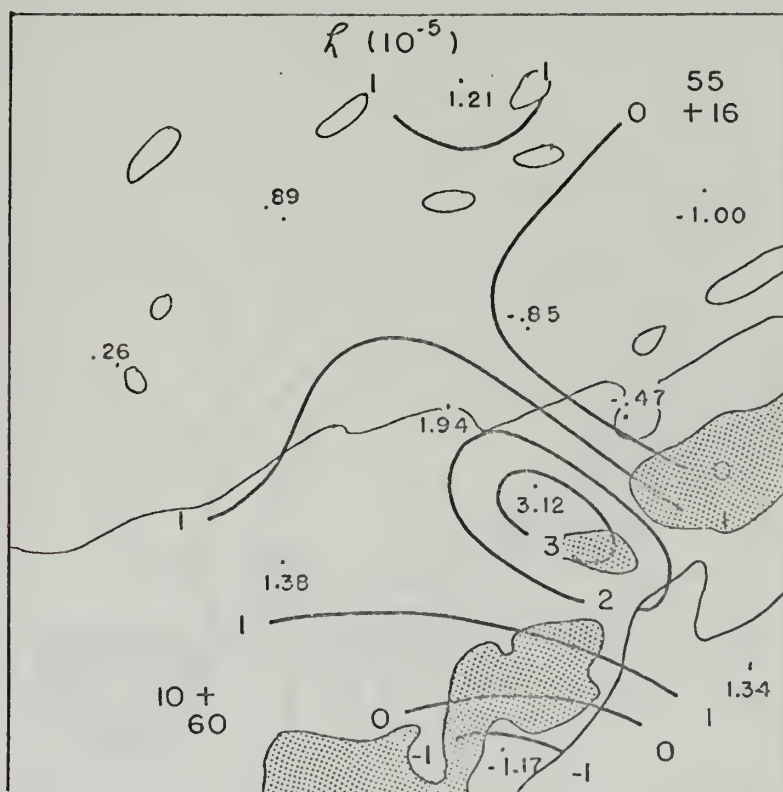


Fig. 8: Same as figure 7 except layer 2.



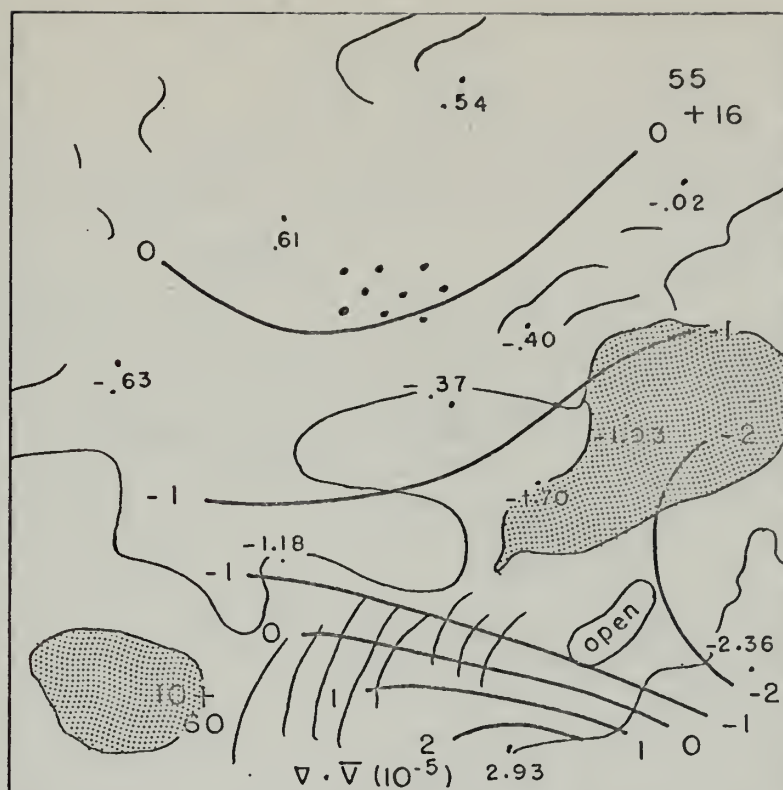
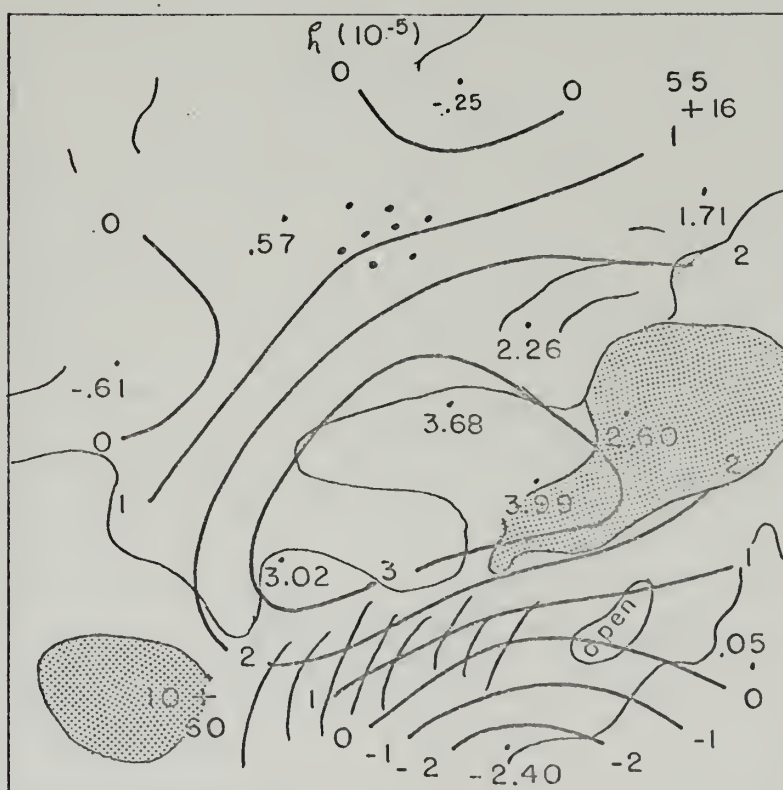


Fig. 9: Analyzed results of divergence and vorticity for 26/00Z, layer 1, with cloud cover for 25/1826Z.



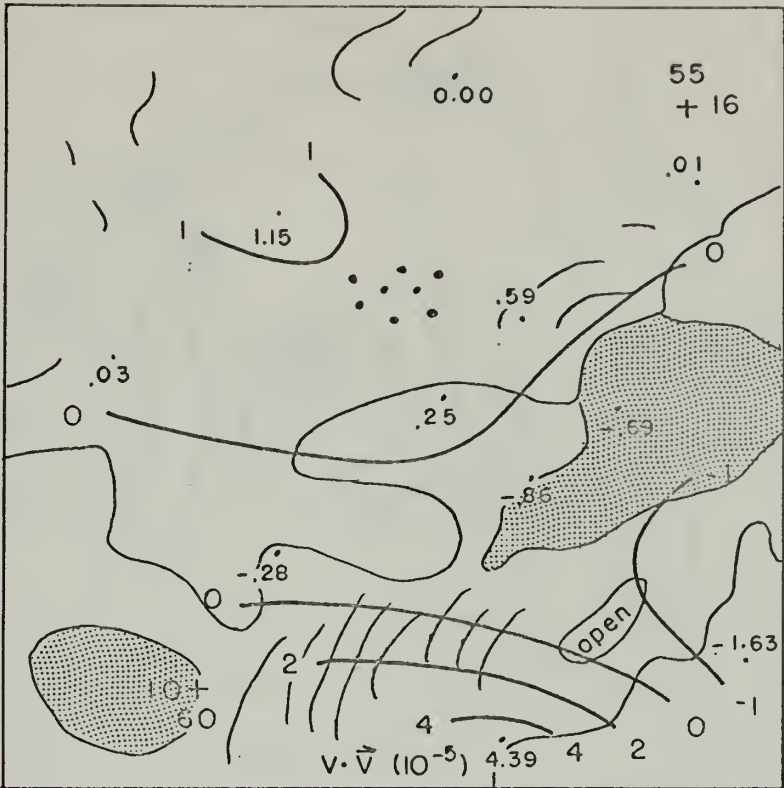
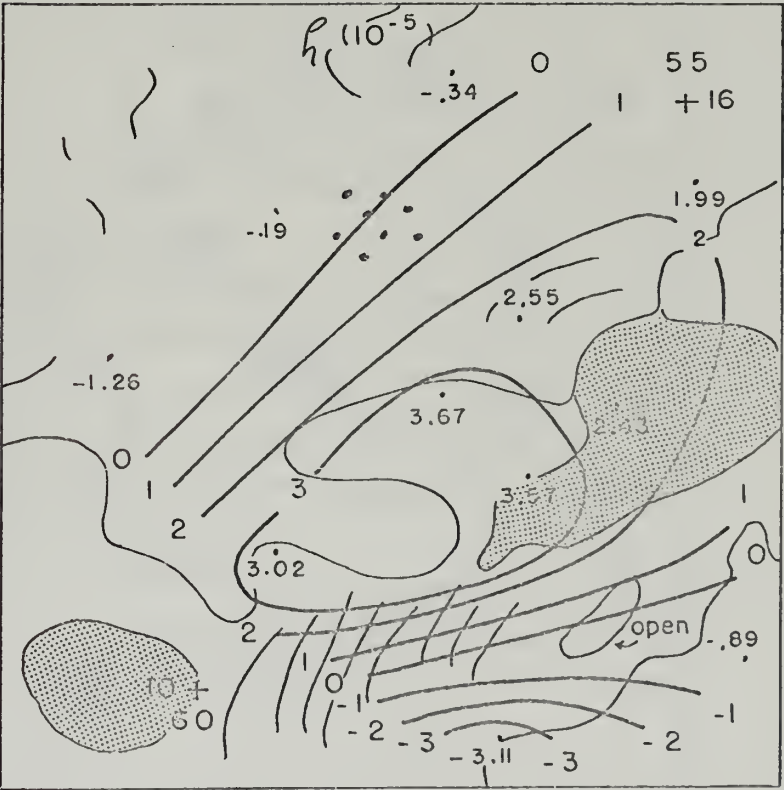


Fig. 10: Same as figure 9 except layer 2.



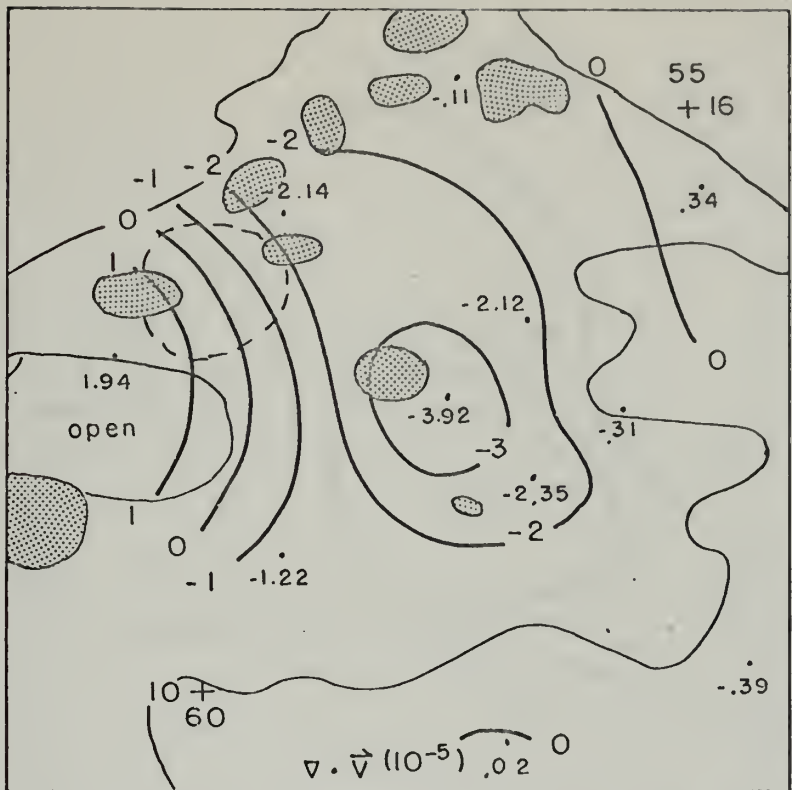
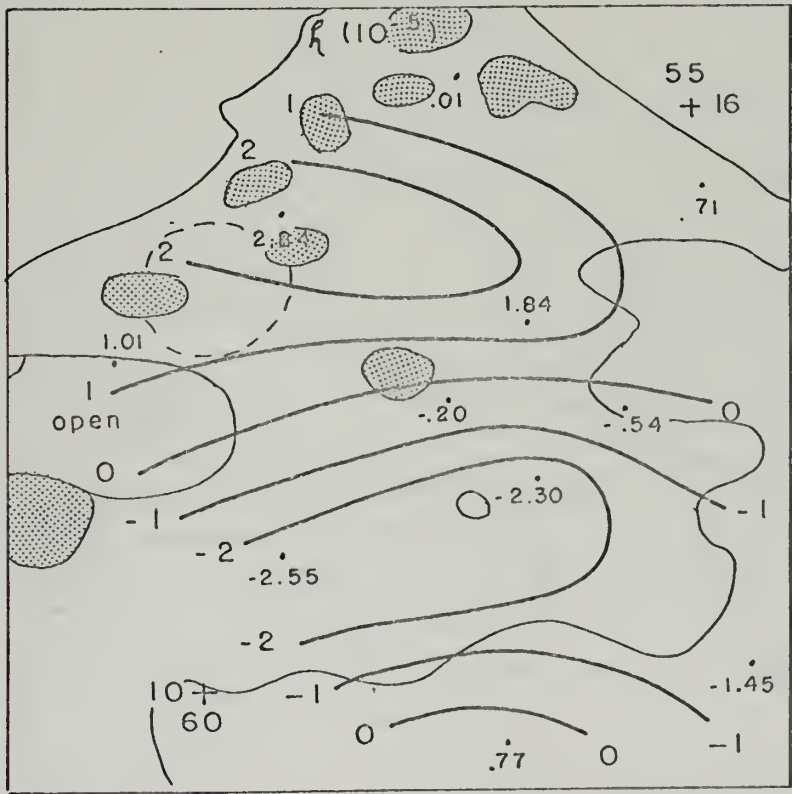


Fig. 11 : Analyzed results of divergence and vorticity for 26/12Z , layer 1, with cloud cover for 26/1233Z .



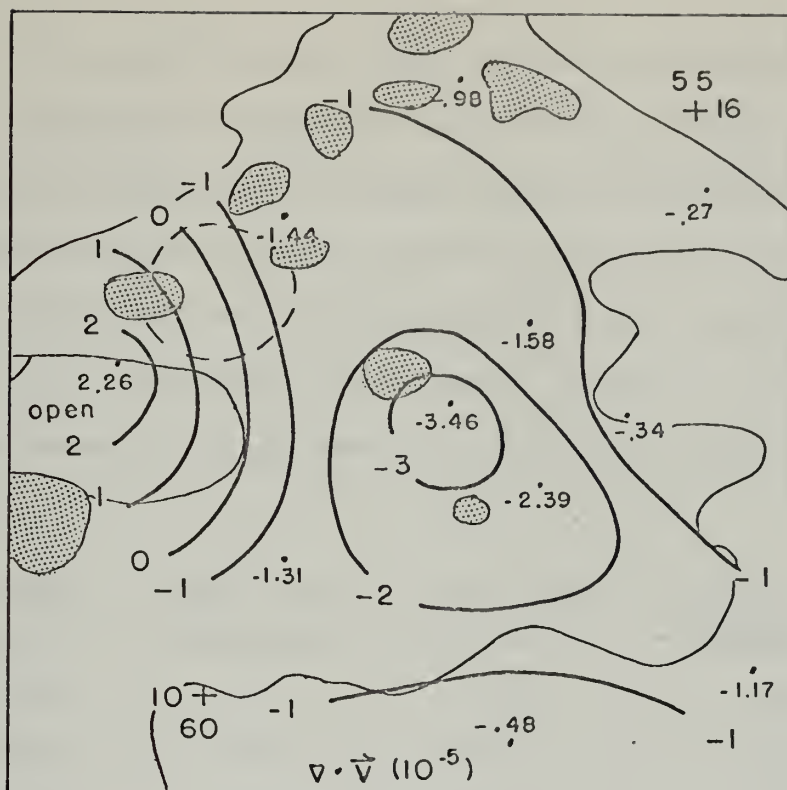
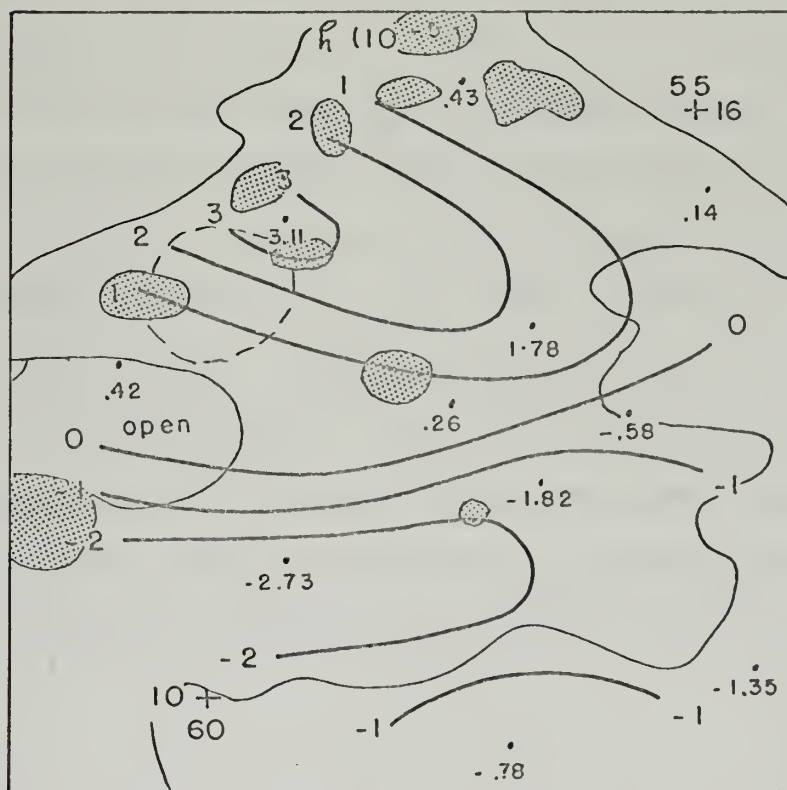


Fig. 12: Same as figure 11 except layer 2.



In order to compare these results with those predicted by Ekman theory, a correlation coefficient between divergence and vorticity was computed. Correlations were computed for all layers to look at differences between layers. To minimize the effects of round-off error, all values were multiplied by 10^5 before computing any means or sums. The results of this are as follows (% with same sign means percent of sample where vorticity and divergence had same sign):

Layer (mb)	Sample Size	% Same Sign	Correlation Coefficient
1000-900	117	43.6	-.19
900-800	117	55.5	-.03
800-700	113	58.4	+.26
700-600	113	56.6	+.15
600-500	109	49.5	-.05
500-400	96	50.0	+.08

These values in the lower layers are somewhat disappointing from what one would expect from Ekman theory. Nevertheless it must be remembered that this is a linear correlation coefficient and as such is merely a measure of the scatter about a best-fit line of the values of divergence and vorticity. Another possibility is that there is a lot of "noise" in the data which was used. It was anticipated that by using layer-mean winds in the computations, instead of winds at discrete levels, much of the unwanted noise or inconsistencies would be minimized. Perhaps the mixing of "A_o" data with teletype data as well as

linearly adjusting the ROCKAWAY's low-level winds contributed to data noise. The low values for the correlation coefficient could have been anticipated from the higher-than-expected percentage (50%) of cases where the divergence and vorticity had the same sign.

The possibility of computing divergence and vorticity on one scale with data contaminated by local small-scale winds may also be a problem. It merely means the assumption of a linear change in the wind between vertices of the triangle does not apply. By using layer-mean winds, however, the effects of such wind regimes should be minimized.

The profiles of the mean values of divergence and vorticity provide an interesting result which is summarized in table 1. (The six samples which were used to obtain the results in table 1 are contained in Appendix B, tables 7-12). The significant fact which is immediately obvious is that the mean (algebraic) divergence is an order of magnitude greater below 800 mb than it is above while the magnitude of the mean (algebraic) vorticity is about the same from 1000 to 400 mb. The sample size is not very large even in the lowest layers where there is more data available, but the maximum values of cyclonic vorticity and convergence do appear to occur in the lowest layers. Furthermore, in the mean, the vorticity and divergence are of opposite sign and are of the same order of magnitude from 1000 to 800 mb.

Table 1 also contains the values of the mean magnitude of divergence and vorticity within each of the six layers. When looked at in this manner the magnitude of the divergence does not decrease

Layer (mb)	Sample Size	$\overline{\xi}$ (10^{-5} sec^{-1})	Variance (10^{-5} sec^{-1})	$\overline{ \xi }$ (10^{-5} sec^{-1})	$\overline{\nabla \cdot \mathbf{W}}$ (10^{-5} sec^{-1})	Variance (10^{-5} sec^{-1})	$\overline{ \nabla \cdot \mathbf{W} }$ (10^{-5} sec^{-1})
1000-900	117	+ .43	1.78	1.11	-.32	1.31	.91
900-800	117	+ .29	2.26	1.23	-.15	1.79	1.02
800-700	113	+ .32	2.18	1.14	-.01	1.34	.88
700-600	113	+ .28	2.06	1.10	+ .01	1.46	.91
600-500	109	- .14	1.56	.97	+ .09	1.69	.97
500-400	96	- .44	1.15	.89	-.04	1.08	.82

Table 1. Summary of mean values of divergence and vorticity.

by a factor of 10 above 800 mb. Comparison of these results with those of Endlich and Mancuso (1963, p. 21) show a tendency for the magnitude of the vorticity to be 5-20% larger than theirs up to 500 mb while the magnitude of the divergence is 20-60% larger than theirs. Above 500 mb the magnitudes of both divergence and vorticity given in table 1 are less than those of Endlich and Mancuso (1963).

Similar computations of algebraic means and mean magnitudes were carried out for each of the three categories of degree of disturbance (U, N and D) and the results are presented in table 2. Although this results in three small samples, particularly for category N, the results between categories do appear to differ dramatically in several respects. The mean (algebraic) vorticity is quite large and cyclonic from 1000 to 600 mb in category D whereas it is weak and anticyclonic in category U. The mean vorticity is also cyclonic from 1000 to 600 mb in category N but not as large as in category D. The variance of the vorticity in category D is quite large and increases from 1000 to 700 mb even though the algebraic mean remains practically constant. The mean (algebraic) divergence also differs considerably between categories U and D. In category U there is very slight convergence but it is an order of magnitude less than the convergence from 1000 to 800 mb in category D. The results for category N appear to be intermediate to those of categories U and D (as would be expected) except for the convergence in layer 3.

To determine if the results in table 2 show any significant differences between categories, the Students t-test (Panofsky and

Category U

Layer (mb)	Sample Size	\bar{P}	Vari- ance	$\overline{ P }$	$\overline{\nabla \cdot W}$	Vari- ance	$\overline{ \nabla \cdot W }$
1000-900	51	-.05	1.12	.89	-.08	.93	.74
900-800	51	-.26	1.76	1.11	0.00	1.09	.83
800-700	50	-.13	1.09	.83	-.04	1.12	.83
700-600	50	.06	1.20	.89	.01	1.72	1.00
600-500	49	-.19	1.37	.87	.08	2.01	1.01
500-400	43	-.75	1.10	1.01	-.13	1.19	.89

Category N

1000-900	24	.56	1.06	.98	-.31	1.67	1.04
900-800	24	.26	1.43	.92	-.24	2.92	1.33
800-700	23	.12	1.70	.90	-.26	2.39	1.17
700-600	23	.12	2.44	1.01	.02	1.53	.82
600-500	23	-.23	1.34	.93	.38	1.45	.92
500-400	21	-.20	.90	.84	.13	1.01	.83

Category D

1000-900	42	.94	2.44	1.46	-.61	1.43	1.05
900-800	42	.98	2.51	1.54	-.27	1.93	1.08
800-700	40	.98	3.10	1.66	.17	.96	.78
700-600	40	.66	2.69	1.41	0.00	1.10	.84
600-500	37	-.02	1.92	1.13	-.08	1.36	.93
500-400	32	-.20	1.01	.75	-.04	.94	.71

Table 2. Summary of mean values of divergence and vorticity within categories of degree of disturbance. Units are 10^{-5} .

Brier, 1958) was performed on the computed means of vorticity and divergence by layers between the three categories. If the results are significant they would be expected to occur between categories U and D.

The results of this test were as follows:

Categories U vs. D

Layer	t_f	% Chance that U=D	$t_{v.w}$	% Chance that U=D
1	3.574	<1	2.333	2
2	4.067	<1	1.071	10-20
3	3.662	<1	.932	10-20
4	2.073	<3	.024	>45
5	.617	25-30	.538	25-30
6	2.204	<3	.363	30-40

Categories U vs. N

Layer	t_f	% Chance that U=N	$t_{v.w}$	% Chance that U=N
1	2.313	<3	.837	20-25
2	1.591	5-10	.753	20-25
3	.859	10-20	.702	20-25
4	.194	40-45	.023	>45
5	.124	45	.884	10-20
6	1.912	2-5	.918	10-20

Categories N vs. D

<u>Layer</u>	<u>t_{ξ}</u>	<u>% Chance that N=D</u>	<u>$t_{\nabla \cdot \nabla}$</u>	<u>% Chance that N=D</u>
1	1.041	10-20	.941	10-20
2	1.926	2-5	.074	>45
3	2.005	1-2	1.313	5-10
4	1.270	10-20	.046	>45
5	.596	25-30	1.451	5-10
6	.029	>45	.619	25-30

The results are evidently very significant. During disturbed conditions there is significantly more cyclonic vorticity than during undisturbed conditions. Furthermore there is significantly more convergence in the lowest layer in disturbed versus undisturbed conditions and the results for convergence in the 900 to 700-mb layers could easily be called meteorologically significant. The results between categories U and N and categories N and D occasionally show significant differences but this is probably caused by the N-sample being a mixture of both U and D values as well as being a small sample. It is interesting to note that there is apparently no significant difference between samples for convergence in the 700 to 600-mb layer because all three samples were essentially non-divergent according to the algebraic mean (see table 2).

The results between categories U and D are in direct support of the CISK hypothesis (Charney and Eliassen, 1964) in that there

is increased cyclonic vorticity and increased convergence in the lowest layers during disturbed conditions. In addition the results presented here indicate the increased cyclonic vorticity is present up to 600 mb whereas the increased convergence occurs up to 800 mb.

CONCLUSIONS

From the results presented in this paper, it appears that the triangular method of computing divergence and vorticity in the tropics yields acceptable results. The contemporary correlations of vorticity and divergence in the lowest layers were disappointing, however the good agreement which was obtained when comparing satellite pictures to analyzed results was encouraging. When the results were divided into categories depending on whether they occurred during disturbed or undisturbed conditions as determined by cloud cover from satellite pictures, there were significant differences between disturbed and undisturbed conditions for both vorticity and divergence. There was a significant increase in cyclonic vorticity and convergence which is in support of the CISK hypothesis (Charney and Eliassen, 1964). Algebraic mean values of divergence and vorticity for the entire sample had the same order of magnitude below 800 mb but the divergence decreased by an order of magnitude above 800 mb. Furthermore the mean (algebraic) vorticity retained the same order of magnitude from 1000 to 400 mb.

It is suggested that additional computations be made of the nature described in the previous sections but without the emphasis on those times when all eight stations reported. Rather the emphasis should be shifted so as to obtain a very large sample of data to determine if the results in tables 1 and 2 remain valid. A more objective method of classifying the results into categories of undisturbed or disturbed is needed. In addition it is not possible from this

study to conclude the reason for the divergence and vorticity having the same sign 50% of the time in the lowest layers, a result which is contradictory to Ekman theory.

Classification of the triangular regions as disturbed or undisturbed might be improved by combining the method used in this study with a method which is more objective. Such a method is available using Θ_e , the equivalent-potential temperature (Rossby, 1932 and Hess, 1959). Garstang et. al. (1967) found that higher values of Θ_e occurred at all levels when the atmosphere was disturbed. In some preliminary reduction of the BOMEX data for 12-15 and 23-28 July 1969 (168 soundings) the author found the vertically-averaged value of Θ_e (surface to 400 mb) to vary from 325.0K to 342.1K, the higher values occurring during disturbed conditions. The advantage of using Θ_e is that it combines the effects of temperature and moisture into one parameter. Furthermore such an objective method could be used by itself for times when no satellite pictures are available. Such an approach might yield results which show more significant differences between the mean divergence and/or vorticity in disturbed and undisturbed conditions. Significant differences (5% level according to Student's t-test) were not found in this study although the differences between the undisturbed versus disturbed divergence in the lowest three layers were significant at 15-35% levels.

Due to the difficulties encountered with the "A₀" data format, it would seem that the teletype data is still the best (most reliable)

data source, even though it's been almost two years since the termination of BOMEX. Since the observers on board the ships are "professionals" at their jobs, it seems reasonable that any corrections which need to be made to the data (e.g. ship motion) would be made by the observers before sending the results of a launch. It is unfortunate that detailed records are not readily available which reflect what corrections, if any, were made by the observers before sending the teletype message.

Since no corrections were made to the winds at the island stations, it is suggested that a method for adjusting the winds reported at these stations be adopted before conducting additional research with triangles affected by these stations. Corrections were suggested by Zipser (1965) for Raizet and Chaguaramas; however the "correction" used by him at Chaguaramas was "ad hoc".

APPENDIX A

The Computation Procedure

Numerous triangles can be formed within the BOMEX array as shown in figure 2 which can be used to calculate horizontal convergence ($\nabla_H \cdot \mathbf{W}$) as shown by Bellamy (1949):

$$\nabla_H \cdot \mathbf{W} = \frac{|\mathbf{W}_A|}{h_A} \sin(\beta_{BC} - d_A) + \frac{|\mathbf{W}_B|}{h_B} \sin(\beta_{CA} - d_B) + \frac{|\mathbf{W}_C|}{h_C} \sin(\beta_{AB} - d_C) \quad (1)$$

where $|\mathbf{W}_i|$ is the observed wind speed, h_i = the altitude of the triangle through vertex i , d_i = the observed wind direction and β_{jK} = the azimuth of the side of the triangle opposite vertex i . With $|\mathbf{W}_i|$ in (m sec^{-1}) and h_i in (m), the units of $\nabla_H \cdot \mathbf{W}$ become sec^{-1} .

Bellamy (1949) describes construction of an overlay to make the necessary computations or, as an alternative, to construct tables which can be entered with wind direction and wind speed. However, with the advent of the electronic computer direct computations using (1) are simplified.

Computations of vorticity can also be performed using (1) if d_i is increased by 90° (Bellamy, 1949), such that

$$\zeta = \sum_{i=1}^3 \frac{|\mathbf{W}_i|}{h_i} \sin(\beta - (d_i + 90)) \quad (2)$$

Since data were used at constant pressure surfaces, the computation of vertical motion with the continuity equation is straightforward.

$$\frac{\partial \omega}{\partial p} = -\nabla \cdot \mathbf{W} \quad (3)$$

Integrating leads to

$$\omega_2 = \omega_1 - \overline{\nabla \cdot \mathbf{V}} \Delta p \quad (4)$$

where the symbol $\overline{(\quad)}$ implies a vertical average.

Using the boundary condition that

$$\omega = 0 \quad \text{at} \quad p = 1000 \text{ mb} \quad (5)$$

enables computation of vertical velocities by successive integrations of (3). (A review of various methods of computing vertical motion are contained in Panofsky [1946]). An additional assumption that $\overline{\nabla \cdot \mathbf{V}} = \nabla \cdot \overline{\mathbf{V}}$ was also made.

APPENDIX B

Table 3. Latitude and longitude of data stations:

<u>Station</u>	<u>Latitude (N)</u>	<u>Longitude (W)</u>
1. Oceanographer	7.5	52.7
2. Mount Mitchell	10.5	56.5
3. Discoverer	13.0	54.0
4. Rockaway	15.3	56.6
5. Rainier	17.5	54.0
6. Barbados	13.1	59.5
7. Raizet	16.3	61.5
8. Chaguaramas	10.7	61.6

Table 4. Designation of triangles:

<u>Triangle No.</u>	<u>Vertices of the triangle</u>
1	Oceanographer, Chaguaramas, Mount Mitchell
2	Oceanographer, Mount Mitchell, Discoverer
3	Mount Mitchell, Chaguaramas, Barbados
4	Mount Mitchell, Barbados, Discoverer
5	Discoverer, Barbados, Rockaway
6	Mount Mitchell, Barbados, Rockaway
7	Mount Mitchell, Rockaway, Discoverer
8	Discoverer, Rockaway, Rainier
9	Rockaway, Raizet, Rainier
10	Barbados, Raizet, Rockaway
11	Chaguaramas, Raizet, Barbados

APPENDIX B

Table 5. Latitude and longitude of triangle centroids:

<u>Triangle No.</u>	<u>Latitude(N)</u>	<u>Longitude(W)</u>
1	9.5	56.9
2	10.3	54.4
3	11.4	59.2
4	12.2	56.6
5	13.8	56.7
6	13.0	57.5
7	12.9	55.7
8	15.2	54.9
9	16.3	57.4
10	14.9	59.2
11	13.4	60.9

APPENDIX B

Table 6: Subjective evaluation of disturbed nature of each triangle for each data time.

U = Undisturbed; D = Disturbed; N = Neither U nor D

This classification was performed independently by two people and the end results compared. The disagreements (5%) were resolved to arrive at this table.

Triangle No.	14/00	14/12	18/00	20/00	21/12	22/12	25/12	26/00	26/12	28/00	28/12
1	D	U	U	N	U	U	D	N	U	U	D
2	D	D	U	N	N	N	N	U	U	U	N
3	U	N	U	U	D	D	D	D	D	U	U
4	U	U	U	D	D	D	D	D	D	U	N
5	U	U	D	D	U	U	U	N	D	D	N
6	U	U	N	D	N	N	N	D	D	N	D
7	U	N	N	D	N	N	N	D	N	D	N
8	U	D	D	U	U	N	U	D	N	D	U
9	U	U	D	U	U	N	U	U	D	D	U
10	U	U	D	U	U	U	U	U	D	D	D
11	U	U	D	U	U	D	U	U	N	D	D

Triangle No.	14/00Z	14/12Z	18/00Z	20/00Z	21/12Z	22/12Z	25/12Z	26/00Z	26/12Z	28/00Z	28/12Z
1	1.22	-0.71	0.02	—	-2.11	—	-2.36	2.93	0.02	-0.04	-0.57
	-1.17	0.76	1.05	—	1.89	—	-0.78	-2.40	0.77	-0.74	0.07
	4.4	-2.6	0.1	—	-7.6	—	-8.5	10.6	0.1	-0.1	-2.1
2	-1.14	0.16	-0.50	—	-0.57	—	-2.32	-2.36	-0.39	1.10	-1.02
	0.78	1.81	0.44	—	0.96	—	2.13	0.05	-1.45	0.70	0.26
	-4.1	0.6	-1.8	—	-2.0	—	-8.4	-8.5	-1.4	4.0	-3.7
3	0.45	-1.35	0.07	-0.39	0.06	-0.27	-0.60	-1.18	-1.22	-0.66	-0.33
	0.90	0.33	1.96	1.22	0.42	3.50	0.86	3.02	-2.55	-0.20	-0.77
	1.6	-4.9	0.2	-1.4	0.2	-1.0	-2.2	-4.3	-4.4	-2.4	-1.2
4	-0.59	-0.36	-0.03	0.78	-0.29	-0.96	-0.95	-1.70	-2.35	1.01	-1.30
	1.89	1.96	0.79	0.37	-0.59	3.06	2.00	3.99	-2.30	1.25	-0.23
	-2.1	-1.3	-0.1	2.8	-1.0	-3.5	-3.4	-6.1	-8.5	3.6	-4.7
5	0.06	-2.33	-0.11	0.97	0.63	0.79	0.13	-0.40	-2.12	-0.49	-1.21
	-2.29	-1.00	0.16	-1.09	-1.18	-1.12	0.05	2.26	1.84	2.19	1.40
	0.2	-8.4	-0.4	3.5	2.3	2.8	0.5	-1.4	-7.6	-1.8	-4.4
6	1.41	-0.12	0.18	1.45	0.39	1.58	0.36	-0.37	-3.92	-0.10	-1.92
	0.13	-0.28	0.45	-0.27	-0.51	1.74	1.49	3.68	-0.20	1.10	0.60
	5.1	-0.4	0.6	5.2	1.4	5.7	1.3	-1.3	-14.1	-0.3	-6.9
7	-2.25	-2.63	-0.36	0.18	-0.15	-2.13	-1.38	-1.93	-0.31	0.78	-0.50
	-0.30	1.54	0.54	-0.38	-1.29	0.35	0.61	2.60	-0.54	2.38	0.46
	-8.1	-9.5	-1.3	0.7	-0.5	-7.7	-5.0	-6.9	-1.1	2.8	-1.8
8	-1.32	-2.66	0.37	0.00	0.78	-0.49	-0.94	-0.02	0.34	-0.48	0.61
	-0.20	1.77	1.01	-0.72	-0.52	0.27	-0.30	1.71	0.71	2.66	-0.52
	-4.8	-9.6	1.3	0.0	2.8	-1.8	-3.4	-0.1	1.2	-1.7	2.2
9	0.75	1.46	0.32	0.25	0.71	1.05	-0.23	0.54	-0.11	0.97	-0.74
	1.83	1.75	0.97	-0.58	0.17	0.84	0.56	-0.25	0.01	0.88	-1.53
	2.7	5.3	1.1	0.9	2.6	3.8	-0.8	1.9	-0.4	3.5	-2.7
10	0.94	0.22	-0.77	1.10	0.07	1.62	1.19	0.61	-2.14	0.82	-1.55
	-1.21	-1.36	0.33	-1.60	-0.45	-1.44	0.34	0.57	2.84	0.36	1.72
	3.4	0.8	-2.8	4.0	0.2	5.8	4.3	2.2	-7.7	2.9	-5.6
11	-0.54	-1.42	-1.39	-1.48	-0.54	-1.42	0.20	-0.63	1.94	0.52	0.70
	-0.66	-1.23	1.99	-0.64	0.44	-0.32	-0.78	-0.61	1.01	-1.32	0.79
	-2.0	-5.1	-5.0	-5.3	-1.9	-5.1	0.7	-2.3	7.0	1.9	2.5

TABLE 7. Results for 1000-900 mb. For each triangle, first line is divergence (10^{-5} sec^{-1}), second line is vorticity (10^{-5} sec^{-1}) and third line is omega (mb hr^{-1}).

Triangle No.	14/00Z	14/12Z	18/00Z	20/00Z	21/12Z	22/12Z	25/12Z	26/00Z	26/12Z	28/00Z	28/12Z
1	-1.38	-1.06	0.38	—	-1.47	—	2.53	4.39	-0.48	-0.75	-0.66
	-0.63	2.31	0.42	—	-0.55	—	-1.17	-3.11	-0.78	-2.00	0.83
2	-0.6	-6.4	1.4	—	-12.9	—	0.6	26.4	-1.7	-2.8	-4.5
	0.07	1.18	-0.28	—	-1.37	—	-2.59	-1.63	-1.17	1.34	-0.71
	0.95	1.68	0.36	—	1.10	—	1.34	-0.89	-1.35	1.45	-0.22
3	-3.8	4.8	-2.8	—	-7.0	—	-17.7	-14.4	-5.6	8.8	-6.2
	0.08	-1.30	0.46	0.12	0.43	-0.85	0.47	-0.28	-1.31	0.30	-0.66
	0.09	-0.05	2.03	0.04	-0.26	2.25	1.38	3.02	-2.73	-1.02	-0.97
4	1.9	-9.5	1.9	-1.0	1.8	-4.0	-0.5	-5.3	-9.1	-1.3	-3.5
	0.95	0.01	0.51	1.41	-0.50	-0.03	-2.38	-0.86	-2.39	2.07	-1.48
	0.64	0.89	0.98	0.19	0.34	1.34	3.12	3.57	-1.82	1.45	-0.99
5	1.3	-1.2	1.7	7.9	-2.8	-3.6	-12.0	-9.2	-17.1	11.1	-10.0
	-0.32	-3.01	-0.15	1.15	0.35	0.02	-0.55	0.59	-1.58	-0.65	-0.39
	-2.20	-2.03	-0.25	-2.27	-1.57	-1.85	-0.85	2.55	1.78	2.43	-0.33
6	-1.0	-19.2	-0.9	7.6	3.5	2.9	-1.5	0.7	-13.3	-4.1	-5.8
	1.48	-0.27	0.68	2.27	0.68	1.28	0.12	0.25	-3.46	0.35	-1.22
	-1.25	-1.75	0.12	-1.10	-0.24	-0.19	1.94	3.67	0.26	0.82	-0.23
7	10.4	-1.4	3.1	13.4	3.9	10.3	1.7	-0.4	-26.6	0.9	-11.3
	-0.95	-2.72	-0.36	0.14	-1.01	-1.51	-3.41	-0.69	-0.34	1.30	-0.68
	-0.05	0.99	0.73	-0.80	-0.92	-0.13	0.47	2.43	-0.58	3.17	-1.21
8	-11.5	-19.3	-2.6	1.2	-4.2	-13.1	-17.2	-9.4	-2.3	7.5	-4.2
	-1.01	-4.17	-0.13	-1.33	-0.01	-0.77	-1.56	0.01	-0.27	-0.38	-0.43
	0.92	1.70	1.05	-1.22	-0.69	1.36	-1.00	1.99	0.14	1.89	-1.38
9	-8.4	-24.6	0.8	-4.8	2.8	-4.5	-9.0	-0.0	0.3	-3.1	0.7
	1.88	1.45	0.61	-0.19	0.79	2.70	-0.25	0.00	-0.98	1.06	-0.80
	2.17	3.48	2.41	0.05	1.42	2.12	1.21	-0.34	0.43	0.80	-0.08
10	9.5	10.5	3.3	0.2	5.4	13.5	-1.7	1.9	-3.9	7.3	-5.6
	0.70	0.48	-0.29	1.90	0.55	1.62	0.93	1.15	-1.44	1.23	-0.16
	-1.57	-1.10	1.06	-2.62	0.34	-1.78	0.89	-0.19	3.11	1.62	1.12
11	5.9	2.5	-3.8	10.8	2.2	11.7	7.6	6.3	-12.9	7.4	-6.2
	-1.19	-0.92	-0.93	-0.91	0.43	-1.58	1.25	0.03	2.26	1.93	0.94
	-0.51	0.13	3.13	-2.10	0.28	-0.11	0.26	-1.26	0.42	-0.40	0.36
	-6.2	-8.4	-8.3	-8.6	-0.4	-10.8	5.2	-2.2	15.1	8.8	5.9

TABLE 8. Results for 900-800 mb. Description the same as for table 7.

Triangle No.	14/00Z	14/12Z	18/00Z	20/00Z	21/12Z	22/12Z	25/12Z	26/00Z	26/12Z	28/00Z	28/12Z
1	-0.32	0.24	-0.13	—	0.07	—	1.96	2.21	-0.70	-0.42	-0.01
	0.27	1.54	0.88	—	-0.76	—	-1.58	-3.53	-1.32	-2.10	0.56
	-1.7	-5.5	1.0	—	-12.6	—	7.7	34.3	-4.2	-4.4	-4.5
2	0.50	0.77	0.07	—	-0.65	—	-2.56	-1.86	-0.51	1.33	-0.63
	0.51	0.57	0.49	—	0.05	—	1.15	-0.14	-0.84	0.50	-0.03
	-2.0	7.6	-2.5	—	-9.3	—	-26.9	-21.1	-7.5	13.6	-8.5
3	-0.20	-0.60	-0.14	-0.21	-0.14	-1.40	0.76	0.49	-1.64	-0.67	0.88
	0.29	-0.71	1.13	0.57	-0.56	0.01	1.30	2.44	-1.63	-0.10	0.35
	1.2	-11.7	1.4	-1.7	1.3	-9.1	2.3	-3.5	-15.0	-3.7	-0.4
4	0.55	-0.58	0.20	0.77	-0.68	-0.22	-1.84	0.02	-1.08	2.01	-0.32
	0.49	0.02	0.61	-0.65	0.20	-0.19	2.70	2.98	-0.54	1.52	-0.55
	3.3	-3.3	2.4	10.6	-5.3	-4.4	-18.6	-9.2	-20.9	18.3	-11.2
5	-1.19	-2.79	0.01	-0.35	-0.84	-1.66	-0.49	-0.07	1.20	-0.02	-0.96
	-1.85	-1.58	-0.93	-2.19	-1.07	-0.83	-1.53	2.05	2.81	3.50	-0.74
	-5.2	-29.3	-0.9	6.4	0.5	-3.1	-3.3	0.4	-9.0	-4.2	-9.2
6	0.65	-1.01	0.72	0.84	-0.25	-0.67	0.52	0.35	-1.33	0.22	-0.56
	-1.35	-1.65	-0.21	-1.86	-0.48	-1.09	1.20	2.50	2.01	1.65	-0.90
	12.7	-5.0	5.7	16.4	3.0	7.9	3.6	0.8	-31.4	1.7	-13.3
7	-1.33	-2.33	-0.60	-0.46	-1.35	-1.17	-3.21	-0.46	1.52	2.03	-0.70
	0.25	0.34	-0.00	-0.82	-0.30	0.19	0.16	2.60	-0.09	3.37	-0.34
	-16.3	-27.6	-4.8	-0.5	-9.0	-17.3	-28.8	-11.1	3.1	14.8	-6.7
8	-0.65	—	-0.66	-1.24	-0.33	-0.37	-0.97	0.79	—	0.30	-1.10
	1.47	—	2.23	-0.71	0.04	3.12	-0.64	2.13	—	3.53	-0.86
	-10.7	—	-1.5	-9.2	1.6	-5.9	-12.5	2.8	—	-2.0	-3.3
9	3.24	—	2.64	1.16	1.55	4.28	1.14	0.94	—	1.30	-0.72
	1.86	—	5.01	-0.16	0.90	1.87	2.06	-0.20	—	1.34	0.03
	21.1	—	12.8	4.4	11.0	28.9	2.4	5.3	—	12.0	-8.2
10	0.61	-0.24	1.33	1.27	0.29	0.52	1.05	0.06	-0.04	1.08	-0.51
	-1.30	-0.88	1.32	-2.25	0.13	-1.54	0.99	0.18	3.09	1.48	0.14
	8.1	1.6	1.0	15.4	3.2	13.5	11.4	6.5	-13.0	11.3	-8.0
11	-0.72	0.06	0.40	-0.61	0.57	-0.62	1.23	-0.27	1.02	0.71	0.76
	0.07	0.04	2.30	-0.26	-0.01	-0.93	1.06	0.18	-0.89	-0.73	1.84
	-8.8	-8.2	-6.9	-10.8	1.6	-13.0	9.6	-3.1	18.8	11.4	8.6

TABLE 9. Results for 800-700 mb. Description the same as for table 7.

Triangle No.	14/00Z	14/12Z	18/00Z	20/00Z	21/12Z	22/12Z	25/12Z	26/00Z	26/12Z	28/00Z	28/12Z
1	-1.72	0.70	-1.53	—	-2.25	—	-0.00	0.99	2.24	1.56	1.64
	-1.43	-0.18	0.32	—	-0.66	—	-1.66	-4.66	-2.55	-0.44	0.07
	-7.9	-3.0	-4.5	—	-20.7	—	7.7	37.9	3.9	1.3	1.4
2	-0.63	-0.49	-0.16	—	0.79	—	-1.17	-1.99	-1.95	1.52	-0.92
	0.66	0.71	0.62	—	0.21	—	0.79	-0.61	-1.40	-0.23	-0.07
	-4.3	5.9	-3.1	—	-6.5	—	-31.1	-28.2	-14.5	19.1	-11.8
3	-0.11	0.18	-0.45	0.47	-0.12	-0.73	1.18	-0.26	-0.53	-1.87	1.95
	-0.94	0.03	-0.57	2.09	-1.87	-1.26	-0.86	0.48	1.53	1.04	0.20
	0.8	-11.0	-0.2	-0.1	0.9	-11.7	6.5	-4.5	-16.9	-10.4	6.6
4	0.18	-0.64	-0.13	-1.45	1.09	0.90	-0.40	-0.32	-1.28	0.73	-0.71
	0.16	0.98	-0.19	0.74	-1.15	-0.71	0.52	1.99	1.41	1.97	-0.28
	3.9	-5.6	2.0	5.4	-1.4	-1.1	-20.0	-10.3	-25.5	21.0	-13.7
5	-1.28	-1.13	0.26	-1.92	-0.01	-2.19	-1.76	0.49	2.25	-0.35	0.75
	-0.92	-1.18	-0.31	-1.56	0.67	-0.01	-0.80	1.05	0.71	4.03	0.66
	-9.9	-33.3	0.1	-0.5	0.5	-10.9	-9.6	2.2	-0.9	-5.4	-6.5
6	-0.10	-0.01	0.10	-0.75	-0.19	-0.89	-0.53	0.45	0.71	-0.63	-0.39
	-0.96	-0.27	-0.10	-0.57	-0.71	-1.62	-0.66	1.87	2.50	2.53	0.77
	12.4	-5.1	6.1	13.7	2.3	4.7	1.7	2.4	-28.8	-0.5	-14.8
7	-0.99	-1.87	-0.01	-2.74	1.44	-0.16	-1.63	-0.40	-0.02	1.21	0.39
	0.35	0.23	-0.43	-0.08	0.18	1.05	0.56	1.19	-0.55	3.41	-0.54
	-19.9	-34.4	-4.8	-10.3	-3.8	-17.9	-34.7	-12.5	3.1	19.1	-5.3
8	-0.83	—	-0.54	-0.41	0.65	-0.28	-0.44	-0.02	—	0.37	-0.40
	0.38	—	1.54	-1.01	0.46	4.17	0.06	0.62	—	4.17	-1.70
	-13.7	—	-3.5	-10.7	3.9	-6.9	-14.0	2.7	—	-0.7	-4.8
9	1.63	—	1.12	2.90	0.72	4.48	2.01	-0.54	—	1.01	-3.52
	0.73	—	4.52	-1.60	1.17	1.53	1.72	1.21	—	0.04	-0.28
	27.0	—	16.9	14.8	13.6	45.0	9.6	3.4	—	15.6	-20.8
10	0.36	0.52	0.73	1.01	0.08	-0.03	-0.01	0.26	1.04	0.36	-0.89
	-0.29	-0.42	2.15	-1.06	1.87	-1.79	1.83	1.37	0.81	0.23	1.54
	9.4	3.5	3.6	19.0	3.5	13.4	11.3	7.5	-9.3	12.6	-11.2
11	0.50	0.61	0.80	1.34	1.05	0.00	2.28	-0.13	-0.24	-0.88	1.77
	-0.37	-0.18	1.42	1.58	0.72	-1.57	2.09	-0.20	-0.65	-1.89	1.80
	-7.1	-6.0	-4.0	-6.0	5.4	-13.0	17.9	-3.6	17.9	8.2	15.0

TABLE 10. Results for 700-600 mb. Description the same as for table 7.

Triangle No.	14/00Z	14/12Z	18/00Z	20/00Z	21/12Z	22/12Z	25/12Z	26/00Z	26/12Z	28/00Z	28/12Z
1	-1.66	0.34	1.69	—	0.19	—	0.62	0.63	1.62	0.42	0.87
	-1.83	-1.38	0.12	—	-1.49	—	-1.15	-2.49	-2.46	0.46	0.62
	-13.9	-1.8	1.5	—	-20.0	—	9.9	40.1	9.7	2.8	4.5
2	-0.79	-0.09	1.43	—	0.55	—	0.57	-1.44	-1.79	-0.13	-0.82
	0.34	0.26	-1.03	—	-0.18	—	-0.64	-0.92	-0.86	0.94	0.39
	-7.2	5.5	2.1	—	-4.5	—	-29.1	-33.4	-20.9	18.6	-14.8
3	-0.27	0.21	0.05	0.05	0.05	0.50	1.31	-0.07	0.14	-1.49	2.61
	-0.14	0.14	-0.50	-0.05	-1.05	-2.05	-1.94	-0.54	0.17	0.90	1.10
	-0.2	-10.2	-0.1	0.1	1.0	-9.9	11.2	-4.7	-16.4	-15.8	16.0
4	0.47	0.48	0.51	—	0.62	0.59	0.47	-0.90	-1.26	-0.76	0.17
	0.45	0.94	-0.55	—	0.08	-0.85	-1.31	0.13	0.77	1.98	-0.29
	5.6	-3.9	3.8	—	0.9	1.0	-18.3	-13.6	-30.1	18.2	-13.1
5	0.81	1.08	-0.29	—	1.49	-2.97	-1.48	1.06	1.65	-2.89	2.91
	0.23	0.53	-0.29	—	2.17	-0.39	0.41	-0.93	0.29	1.26	-0.73
	-7.0	-29.5	-1.0	—	5.8	-21.6	-14.9	6.0	5.0	-15.9	3.9
6	0.72	0.93	0.01	-0.55	0.20	-1.33	-1.17	0.48	0.34	-1.51	1.67
	0.47	0.98	-0.74	-1.25	1.44	-2.07	-1.27	0.41	1.72	0.76	0.61
	15.0	-1.7	6.1	11.8	3.0	-0.1	-2.5	4.2	-27.6	-6.0	-8.7
7	0.52	0.56	0.27	—	1.99	-0.80	0.39	-0.51	-0.17	-2.05	1.20
	0.19	0.48	-0.06	—	0.62	1.02	0.38	-1.27	-0.80	2.65	-1.77
	-18.0	-32.3	-3.8	—	3.3	-20.7	-33.2	-14.3	2.4	11.7	-1.0
8	0.31	—	-1.46	—	1.87	-0.41	0.21	-1.13	—	0.36	-0.30
	-0.64	—	1.58	—	-0.83	2.81	0.36	-2.80	—	2.68	-4.23
	-12.6	—	-8.7	—	10.7	-8.4	-13.3	-1.3	—	0.6	-5.9
9	-0.15	—	-0.95	2.12	-1.03	3.53	0.76	-3.29	—	3.26	-5.29
	-0.50	—	2.64	-2.14	-0.99	-0.24	-1.28	0.15	—	-1.43	-0.56
	26.5	—	13.5	22.4	9.8	57.7	12.4	-8.5	—	27.4	-39.9
10	0.95	0.95	-0.87	-0.35	0.38	-1.09	-1.00	0.14	0.73	-0.97	0.20
	0.14	0.68	-0.15	-1.20	2.48	-2.09	-0.17	0.84	0.64	-0.92	1.20
	12.8	6.9	0.5	17.8	4.9	9.5	7.7	8.0	-6.6	9.1	-10.5
11	0.09	0.43	-0.80	-0.10	1.21	0.72	1.92	-0.04	0.78	-1.34	1.09
	-0.83	-0.39	0.30	0.13	-0.07	-1.57	-0.10	-0.20	-1.07	-0.93	2.31
	-6.7	-4.5	-6.9	-6.3	9.8	-10.4	24.8	-3.8	20.7	3.4	18.9

7.

TABLE 11. Results for 600-500 mb. Description the same as for table

	14/00Z	14/12Z	18/00Z	20/00Z	21/12Z	22/12Z	25/12Z	26/00Z	26/12Z	28/00Z	28/12Z
1	0.20	1.38	—	—	1.16	—	2.73	1.35	0.52	0.60	-0.22
	-1.64	-2.04	—	—	-1.82	—	-2.62	-1.07	-1.94	-0.12	-0.19
	-13.2	3.2	—	—	-15.9	—	19.7	45.0	11.6	4.9	3.7
2	0.01	0.14	—	—	-0.78	—	-0.19	—	-1.31	-1.11	0.58
	-0.03	-0.61	—	—	-0.43	—	-2.20	—	-0.65	-0.79	0.29
	-7.1	6.0	—	—	-7.3	—	-29.7	—	-25.6	14.6	-12.7
3	-0.45	0.97	0.12	-1.09	0.55	0.01	0.63	-0.04	0.69	-0.39	1.03
	-0.67	-0.33	-1.19	-1.59	0.00	-1.27	0.36	0.80	-0.31	-0.29	-0.82
	-1.8	-6.8	0.4	-3.8	3.0	-9.9	13.5	-4.9	-13.9	-17.2	19.8
4	0.10	0.69	—	—	-0.25	-0.20	0.29	—	-0.53	-1.56	0.80
	0.66	0.24	—	—	0.53	-1.65	-0.11	—	-0.13	-0.49	-0.53
	6.0	-1.4	—	—	-0.0	0.3	-17.3	—	-32.0	12.6	-10.2
5	0.04	-1.42	—	—	1.31	-0.74	1.34	—	0.24	-2.06	-1.35
	0.08	0.22	—	—	-0.56	-0.51	1.72	—	1.87	0.31	1.12
	-6.8	-34.6	—	—	10.5	-24.3	-10.1	—	5.9	-23.3	-0.9
6	0.30	-0.33	-1.45	-0.85	0.94	-0.93	0.05	0.21	-0.98	-2.13	-0.91
	0.35	-0.63	-1.34	-1.09	0.63	-1.32	1.21	1.16	1.15	-0.30	-0.60
	16.1	-2.9	0.9	8.7	6.4	-3.5	-2.3	4.9	-31.1	-13.6	-12.0
7	-0.19	-0.27	—	—	-0.06	0.09	1.62	—	0.75	-1.42	0.60
	0.43	1.22	—	—	-0.69	-0.89	0.22	—	0.41	0.10	1.22
	-18.7	-33.3	—	—	3.1	-20.4	-27.4	—	5.2	6.6	1.1
8	-0.72	—	—	—	0.47	-0.20	0.99	—	—	0.92	—
	0.25	—	—	—	-1.84	0.40	-1.25	—	—	0.26	—
	-15.2	—	—	—	12.3	-9.1	-9.7	—	—	3.9	—
9	0.60	—	0.52	1.03	-0.74	0.80	-3.17	-3.24	—	1.49	—
	0.24	—	-0.18	-2.96	-0.43	-1.04	-3.91	-2.44	—	-2.23	—
	28.6	—	15.3	26.1	7.2	60.6	1.0	-20.2	—	32.7	—
10	1.41	-0.45	-1.66	-0.64	0.91	-0.28	-0.87	-0.80	-0.32	-1.68	-0.87
	-0.36	-0.13	-0.67	-1.49	0.47	-1.72	-1.13	0.28	0.25	-0.30	0.80
	17.9	5.3	-5.5	15.4	8.2	8.5	4.6	5.1	-7.8	3.0	-13.6
11	0.85	0.86	-0.00	-0.81	0.68	0.57	-0.54	-1.14	1.62	0.06	1.43
	-1.86	0.59	0.01	-2.13	-0.28	-1.54	-1.66	0.04	-0.85	0.14	1.18
	-3.7	-1.4	-6.9	-9.3	12.2	-8.4	22.8	-7.9	26.6	3.6	24.1

TABLE 12. Results for 500-400 mb. Description the same as for table 7.

REFERENCES

- Arnason, G., 1955: Large scale vertical velocity and horizontal divergence. M.I.T. Tech. Rept. No. 16.
- Arnason, G., K.D. Hage and G.M. Howe, 1963: Theoretical and synoptic studies of low-level tropical perturbations. Final report, U.S. Weather Bureau, Contract CWB-10499, The Travelers Research Center, Inc., Hartford, Oct. 1963, 87 pp.
- Bellamy, J.C., 1949: Objective calculations of divergence, vertical velocity and vorticity. Bull. Amer. Meteor. Soc., 30, 45-49.
- BOMAP, 1971: Temporary BOMEX data archive documentation, Doc. -1, (on microfilm). See P. 44 of BOMEX bulletin No. 9 for availability.
- BOMEX bulletin No. 1, not dated: Prepared by the BOMEX Project Office, U.S. Dept. of Commerce, ESSA, Rockville, Md.
- BOMEX bulletin No. 2, 14 May 1968: Prepared by the BOMEX Project Office, U.S. Dept. of Commerce, ESSA, Rockville, Md.
- BOMEX bulletin No. 3, 27 Jan. 1969: Prepared by the BOMEX Project Office, U.S. Dept. of Commerce, ESSA, Rockville, Md.
- BOMEX bulletin No. 4, 1 May 1969: Prepared by the BOMEX Project Office, U.S. Dept. of Commerce, ESSA, Rockville, Md.
- BOMEX bulletin No. 5, November 1969: Prepared by the BOMAP Office, U.S. Dept. of Commerce, ESSA, Rockville, Md. 20852
- BOMEX bulletin No. 6, March 1970: Prepared by the BOMAP Office, U.S. Dept. of Commerce, ESSA, Rockville, Md. 20852
- BOMEX bulletin No. 7, July 1970: Prepared by the BOMAP Office, U.S. Dept. of Commerce, ESSA, Rockville, Md. 20852
- BOMEX bulletin No. 8, October 1970: Prepared by the BOMAP Office, U.S. Dept. of Commerce, NOAA, Rockville, Md. 20852
- BOMEX bulletin No. 9, January 1971: Prepared by the BOMAP Office, U.S. Dept. of Commerce, NOAA, Rockville, Md. 20852

- Byers, H.R. and H.R. Rodebush, 1948: Causes of thunderstorms of the Florida peninsula. *J. Meteor.* 5, 275-280.
- Byers, H.R. and E.C. Hull, 1949: Inflow patterns of thunderstorms as shown by winds aloft. *Bull. Amer. Meteor. Soc.*, 30, 90-96.
- Charney, J.G. and A. Eliassen, 1964: On the growth of the hurricane depression. *J. Atmos. Sci.*, 21, 68-75.
- Charney, J.G., 1969: A further note on large-scale motions in the tropics. *J. Atmos. Sci.*, 26, 182-185.
- Cook, A., 1969: The Barbados story. ESSA world, U.S. Dept. of Commerce, ESSA, October 1969.
- Davidson, B., 1968: The Barbados oceanographic and meteorological experiment. *Bull. Amer. Meteor. Soc.*, 49, 928-934.
- Endlich, R.M. and R.L. Mancuso, 1963: Objective and dynamical studies of tropical weather phenomena. Final report to U.S. Army ERDL, Contract No. DA36-039 SC-89092, Stanford Research Institute, Menlo Park, Cal., August 1963, 47 pp.
- Fernandez-Partagas, J.J. and M.A. Estoque, 1970: A preliminary report on meteorological conditions during BOMEX, fourth phase (July 11-28, 1969). Report prepared for National Science Foundation under Grant No. NSF GA 10201. Rosen-
tiel School of Marine and Atmospheric Sciences, Div.
of Atmospheric Sciences, University of Miami, Coral
Gables, 95 pp.
- Friedman, H.A. and J.D. McFadden, 1970: ESSA research flight facility aircraft participation in the Barbados oceanographic and meteorological experiment. *Bull. Amer. Meteor. Soc.* 51, 822-834.
- Garstang, Michael, Noel E. La Seur and Carl Aspliden, 1967: Equivalent potential temperature as a measure of the structure of the tropical atmosphere. Final report to U.S. Army Electronics Research and Development Laboratory, Rept. No. 67-10, Dept. Meteor. , Florida State Univ., 44 pp.
- Graham, R.D., 1953: A new method of computing vorticity and divergence. *Bull. Amer. Soc.*, 35, 68-74.

- Gray, W.M., 1968: Global view of the origin of tropical disturbances and storms. *Mon. Wea. Rev.*, 96, 669-700.
- Hess, S.L., 1959: Introduction to theoretical meteorology. New York, Holt, Rinehart and Winston, 355 pp.
- Holland, J.Z., 1970: Preliminary report on the BOMEX sea-air interaction program. *Bull. Amer. Meteor. Soc.*, 51, 809-820.
- Kuettner, J.P. and J. Holland, 1969: The BOMEX project. *Bull. Amer. Meteor. Soc.*, 50, 394-402.
- Kyle, A.C., 1970: Longitudinal variation of large scale vertical motion in the tropics. S.M. thesis, Mass. Inst. of Tech., 56 pp.
- Landers, H., 1955: A three-dimensional study of the horizontal velocity divergence. *J. Meteor.*, 12, 415-427.
- Lateef, M.A., 1967: Vertical motion, divergence and vorticity in the troposphere over the Caribbean, August 3-5, 1963. *Mon. Wea. Rev.*, 95, 778-790.
- Lilly, D.K. and N.E. LaSeur, 1956: A statistical study of some Caribbean wind data. Scientific Report No. 3, AFCRC-TN-56-679, Dept. of Meteor., Florida State Univ., 34 pp plus figures.
- Manabe, S., J.L. Holloway, Jr. and H.M. Stone, 1970: Tropical circulation in a time-integration of a global model of the atmosphere. *J. Atmos. Sci.*, 27, 580-613.
- Panofsky, H.A. and G.W. Brier, 1958: Some applications of statistics to meteorology. University Park, Pennsylvania, The Pennsylvania State Univ., 224 pp.
- Panofsky, H.A., 1946: Methods of computing vertical motion in the atmosphere. *J. Meteor.*, 3, 45-49.
- Riehl, H., 1954: Tropical meteorology. New York, McGraw-Hill, 392 pp.
- Rossby, C.-G., 1932: Thermodynamics applied to air mass analysis. M.I.T. Meteor. Papers, Vol. 1, No. 3, 48 pp.

- Sargeant, D. and S. Ruttenberg, 1970: Workshop on tropical experiments, Miami, 22-24 June 1970. A preliminary summary prepared for the executive committee meeting of the U.S. GARP committee, 2 July 1970, 9 pp.
- Schact, E.J., 1946: A mean hurricane sounding for the Caribbean area. Bull. Amer. Meteor. Soc., 27, 324-327.
- U.S. Dept. of Commerce, 1969: Where the air meets the sea. ESSA World, U.S. Dept. of Commerce, ESSA, July, 1969.
- Zipser, E.J., 1965: The distribution and depth of convective clouds over the tropical Atlantic ocean, as determined from meteorological satellite and other data. Ph. D. dissertation, Florida State Univ., 153 pp.
- Zipser, E.J., 1970: The line islands experiment, its place in tropical meteorology and the rise of the fourth school of thought. GARP topics No. 15. Bull. Amer. Meteor. Soc., 51, 1136-1146.

27 AUG 72

19772

Thesis

A444

Anawalt

Kinematic studies
of BOMEX - Phase IV.

128266

24 SEP 71
27 AUG 72

DISPLAY
19772

Thesis

A444

Anawalt

Kinematic studies
of BOMEX - Phase IV.

128266

thesA444

Kinematic studies of BOMEX :



3 2768 001 91467 4

DUDLEY KNOX LIBRARY